The TREND IN ENGINEERING

at the University of Washington

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PROFESSIONAL ETHICS AND ENGINEERING EDUCATION

A Guest Editorial

A. ARTHUR HEMENWAY

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INTEREST in engineering professional ethics has reached an all-time high, judging from the popularity of the subject for articles in engineering journals, for addresses before professional groups, and for committee investigations Various organizations, such as the American Society for Engineering Education, the Engineering Council for Professional Development, and others, have endeavored to establish standards for professional ethics and to recommend programs for achieving such standards. Inevitably, these programs would shift to engineering educators the task of preparing engineering graduates to conduct themselves in accordance with high standards of professional ethics as well as moral behavior in general.

Teaching professional engineering ethics might seem to be just one more requirement added to all the other tasks expected of engineering colleges. However, the special nature of the pedagogical problem involved in teaching any kind of ethics does not appear to be sufficiently understood. Stated very simply, the objective would seem to be to teach engineering students to think and act like the wisest and most experienced members of our profession If this is the objective, we should then ask, "How did *they get that way?*"

The answer might be a combination of a propitious childhood environment with the development of a mature philosophy during many years of experience. A superior sense of professional ethics can come only from a superior sense of values. For a philosopher, the term "ethics" implies "values," and values are more a matter of wisdom than of knowledge.

This faces us with our pedagogical problem, "How can we teach an engineering student to be mature and wise?" Neither the student's personal sense of values nor his moral behavior can be significantly matured or influenced by a series of lectures and examinations. His response will be negligible even to the appeal of self-interest: "We're all engineers together trying to raise professional standards, and it's up to you to contribute your fair share."

The technical achievements of our country speak eloquently of the success of our science and engineering educators in teaching facts and methods. The mental discipline of engineering education certainly improves the thinking habits of students faced with technical problems. We know that the graduate engineer successfully transfers his problem-solving skills to his professional work, and that he will certainly utilize the solutions he obtains. However, there is no reason to believe that an engineer will utilize in his personal behavior any facts or reasoning techniques learned from classroom ethics. Psychologists say that behavior is almost entirely determined by patterns of activity developed from childhood in the course of many thousands of specific instances. University of Washington's Dean Emeritus Edwin R. Guthrie says, "What we do is what we have learned through previous doing and not through listening. A course in which engineering ethics is taught or discussed would not develop skills in ethical behavior but might develop skills in talking about ethics." Apparently, then, it is unreasonable to expect educators to teach engineering students to think and act like the wisest and most experienced members of our profession.

If we initially set our sights too high, if our original objective was unrealistic, is there any teaching activity relevant to our problem? The answer lies in the identification of the terms "ethics" and "values." Given some stimulus to develop a superior sense of values, the engineering graduate may begin to question himself concerning his personal behavior and professional ethics. That this activity of self-questioning will begin in youth and increase with years of experience is, perhaps, the most we can hope for. Self-questioning, self-evaluation, self-knowledge: these are all general objectives of a liberal education. All liberal arts courses are supposed to be concerned with these objectives, and one of the distinctive characteristics of the first-rate engineering teacher is that he will consider a technical subject from a standpoint of values whenever it is appropriate to do so.

Unfortunately, opportunities for introducing values into engineering courses are limited, and student encounters with engineering teachers who stress values are a matter of chance. Even in liberal arts courses, where consideration of values is a planned objective, the teacher may neglect them. This suggests the advisability of requiring every engineering student to attend a course with values as its primary subject matter, to ensure some minimum of coverage. Such a course might first review the origin and development of ideas of right and wrong, good and bad, beautiful and ugly. Second, it should consider the ethical ideas of various religions and customs in different parts of the world during the course of history up to the present time. Finally, most of the teaching time should be devoted to the concept of values in human thinking. An understanding of the distinction between thinking which attempts to explain facts and thinking which attempts to set values will be useful to an engineer in making technical decisions, even if his social behavior should be opprobrious. For maximum results in a minimum of time, the required course suggested here should be confined to fundamental concepts.

Who should teach such a course so that it will stimulate a student's interest in values? To be successful, it should probably be taught by competent philosophy teachers, and not by graduate students or even by humanities teachers whose special training has been in other fields. Even as we expect people who want a bridge to seek assistance from engineers, and sick people to visit physicians, so should we turn for assistance in basic ethics teaching to those who have made it a life work. To find competent philosophy teachers for a course in basic ethics would actually be easier than to find teachers for a synthetic course in professional or "applied" ethics.

Perhaps the requirement that engineering students attend a fundamental ethics course might be the best evidence that the engineering profession has a serious long-range interest in improving its ethical standards.

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* The writer has been with the Boeing Airplane Company since 1940, with the exception of 1947-1949 when he was Assistant Professor of Humanistic-Social Studies at the University of Washington.

The University's new nuclear reactor (See page 17)

THE ENGINEERING EXPERIMENT STATION announces the availability of research assistantantships for 1958-59. Research opportunities are offered in all branches of engineering, including nuclear engineering.

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for

1958-1959

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Civil

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ENGINEERING

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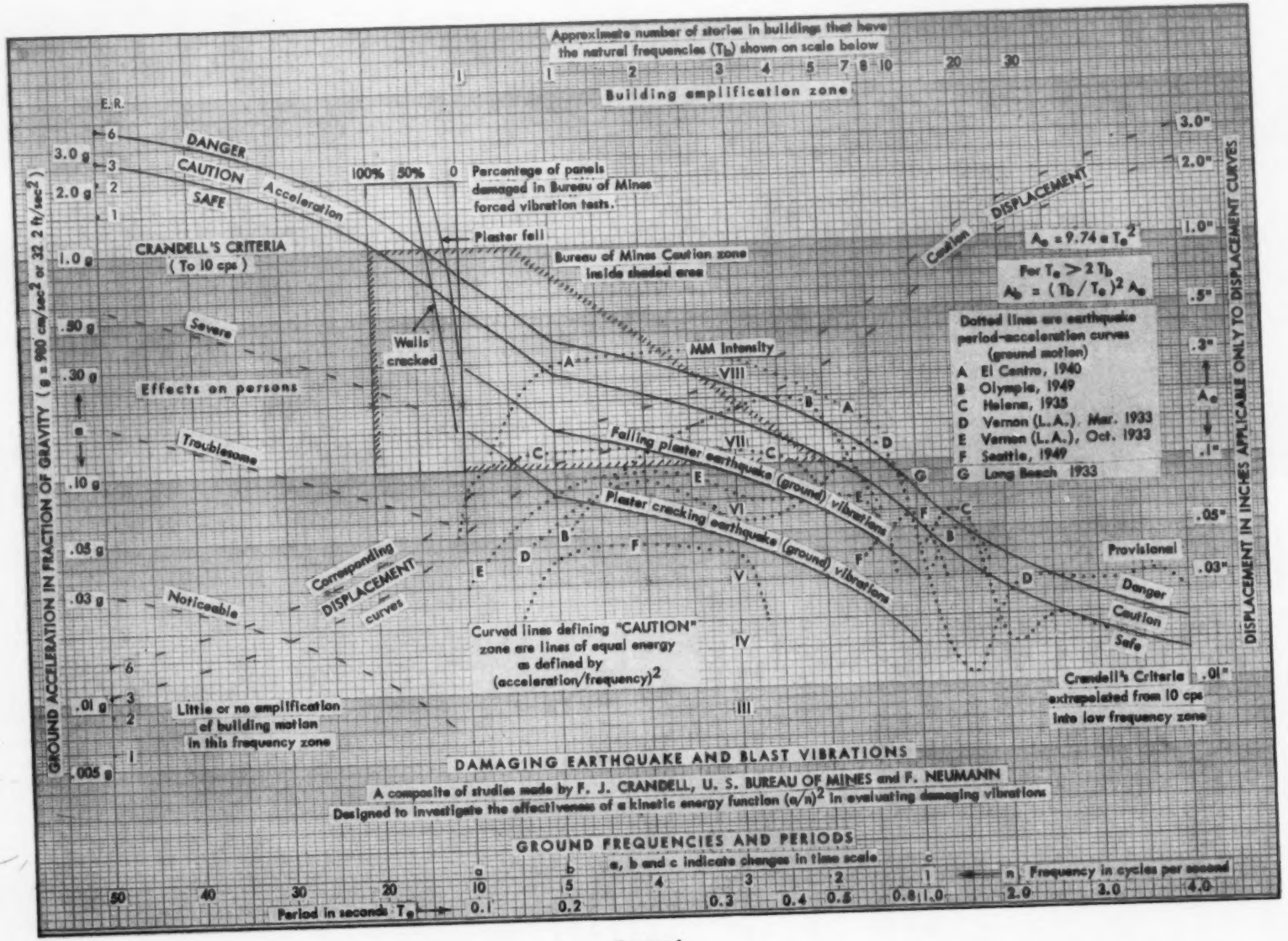
Approximate number of stories in buildings that have the natural frequencies (T_b) shown on scale below
Building amplification zone
E.R.
DANGER
CAUTION
SAFE
Acceleration
CRANDELL'S CRITERIA
(To 10 cps)
Severe
Troublesome
Noticeable
Effects on persons
Little or no amplification of building motion in this frequency zone
100% 50% 0 Percentage of panels damaged in Bureau of Mines forced vibration tests.
Plaster fell
Walls cracked
Bureau of Mines Caution zone inside shaded area
MM Intensity
VIII
VII
VI
V
IV
III
Falling plaster earthquake (ground) vibrations
Plaster cracking earthquake (ground) vibrations
Corresponding DISPLACEMENT curves
Curved lines defining "CAUTION" zone are lines of equal energy as defined by (acceleration/frequency)^2
Caution
DISPLACEMENT
$A_e = 9.74\, a\, T_e^2$
For $T_e > 2\, T_b$
$A_b = (T_b / T_e)^2 A_e$
Dotted lines are earthquake period-acceleration curves (ground motion)
A El Centro, 1940
B Olympia, 1949
C Helena, 1935
D Vernon (L.A.), Mar. 1933
E Vernon (L.A.), Oct. 1933
F Seattle, 1949
G Long Beach 1933
Provisional
Danger
Caution
Safe
Crandell's Criteria extrapolated from 10 cps into low frequency zone
DISPLACEMENT IN INCHES APPLICABLE ONLY TO DISPLACEMENT CURVES
GROUND ACCELERATION IN FRACTION OF GRAVITY (g = 980 cm/sec^2 or 32.2 ft/sec^2)
DAMAGING EARTHQUAKE AND BLAST VIBRATIONS
A composite of studies made by F. J. CRANDELL, U. S. BUREAU OF MINES and F. NEUMANN
Designed to investigate the effectiveness of a kinetic energy function $(a/n)^2$ in evaluating damaging vibrations
GROUND FREQUENCIES AND PERIODS
a, b and c indicate changes in time scale
n, Frequency in cycles per second
Period in seconds T_e

FIGURE 1

DAMAGING EARTHQUAKE AND BLAST VIBRATIONS

FRANK NEUMANN
Seismologist, Department of Geology

Frank Neumann

The world of business and engineering has long been waiting for an acceptable answer to the question, "What is a damaging ground vibration?" The most difficult vibrations to analyze and relate to damage are earthquake and blast vibrations because of their great complexity. It is the exception rather than the rule to find such vibrations of rhythmic or simple harmonic character. The analyst, however, is obliged to discuss such vibrations in terms of frequency, period, and amplitude in order to simplify the problem and make it understandable to interested readers who often may have only nominal background in the physical sciences. Broadly speaking, these complex vibrations may be considered combinations of the simpler wave forms, and it is in this sense that they are analyzed by many investigators, including the writer.

This paper is primarily an effort to reconcile certain conclusions reached on damaging vibrations by three investigators, but in this process some new concepts in analytical methods were developed that will also be discussed. In 1949, F. J. Crandell published, in the *Journal of the Boston Society of Civil Engineers,* a paper entitled "Ground Vibration Due to Blasting and Its Effect upon Structures," which covers better than either of the others the very high frequency blast vibrations obtained at short distances. In 1942, the U. S. Bureau of Mines issued Bulletin 442, by J. R. Thoenen and S. L. Windes, entitled "Seismic Effects of Quarry Blasting," which gives the results of blast vibration measurements made with both small and large weights of explosives over a wide range of distances. In 1952, the writer, through the University of Washington Press, published a booklet entitled "Earthquake Intensity and Related Ground Motion" which, in part, analyzes a group of seismographic records of damaging earthquake motions obtained by the U. S. Coast and Geodetic Survey. In all of these studies, the question of building damage and nature and magnitude of the vibration that causes it are matters of primary interest. On the surface, however, there appear to be serious discrepancies between these reports, and these, together with many other statements found in the literature on the subject, require further discussion. Figure 1 summarizes graphically many of the ideas presented in these three papers.

Displacement and Acceleration Records

The simplest type of vibration record to understand is one that registers the displacement or "amplitude" of the ground motion in inches or centimeters. At any instant during the vibration one can see how much the ground or building is displaced from its normal zero position. If one displacement meter is operated in the basement of a building and another one on the top floor during an earthquake or blast, it is possible to measure, at least in part, the amount of distortion, deformation, or flexure that the building experiences.

But the natural period of a displacement seismograph pendulum must be longer than any of the ground or building periods it is expected to register. This requires a large pendulum, the mass of which remains fixed in space while the ground or building vibrates beneath it, a pendulum sensitive to tilting motions, and, hence, one that is unwieldly and yet delicate. During earthquakes, moreover, the range of amplitudes associated with high-frequency waves (very small) and with long-period waves (very large) is so great that they cannot be registered with legible amplitudes on an ordinary seismograph record. If the large-amplitude, long-period waves are legibly recorded, then the amplitudes of the high-frequency waves are generally too small to be seen on the same record. One must be prepared in vibration studies to measure amplitudes ranging from one-thousandth of an inch up to several inches. Thus while displacement records are satisfactory for recording the relative displacements or distortion between the various floors of a structure, they reveal, in themselves, nothing about the "force" of the vibration; and from the instrumental viewpoint, they have practical disadvantages over other types of vibration-measuring instruments.

If an earthquake or blast vibration is measured with a pendulum that has a frequency higher than any of the frequencies to be measured, such a seismograph would measure the acceleration of the motion. The amplitude on the accelerograph record at any instant would represent the acceleration at that instant. On such a record it is usually impossible to recognize the point where maximum displacement occurs because maximum displacement waves are

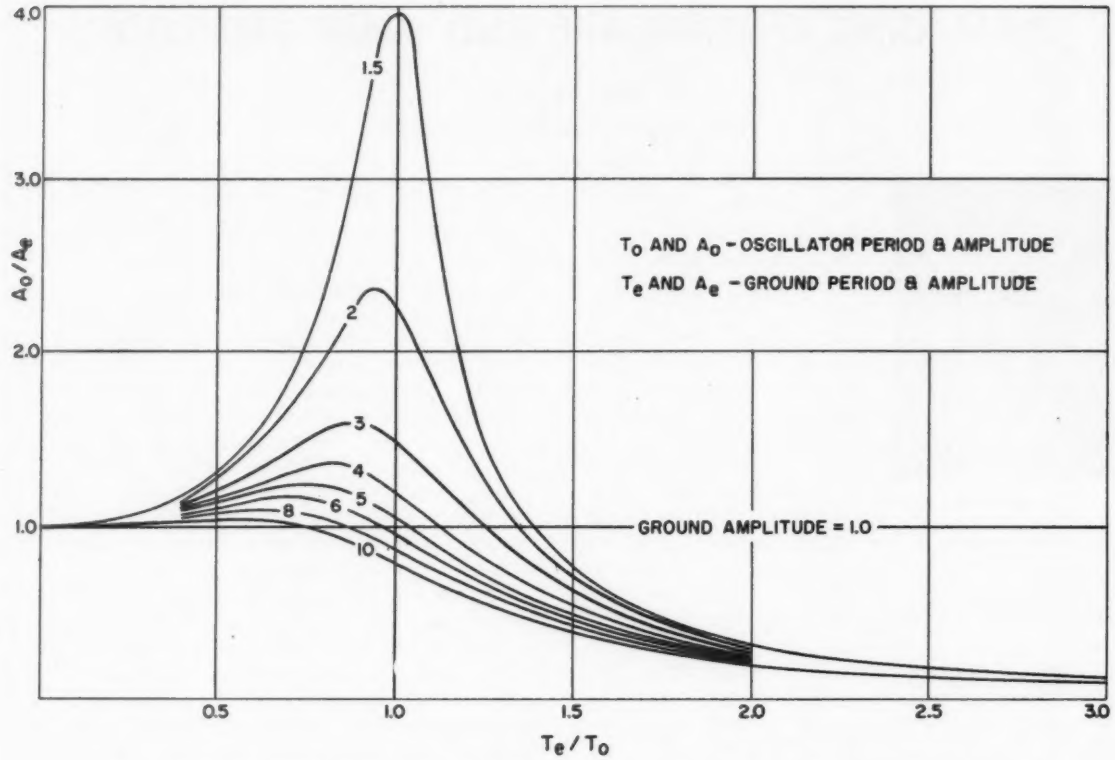

FIG. 2. AMPLIFICATION CURVES FOR FORCED STEADY-STATE VIBRATIONS OF DAMPED OSCILLATORS

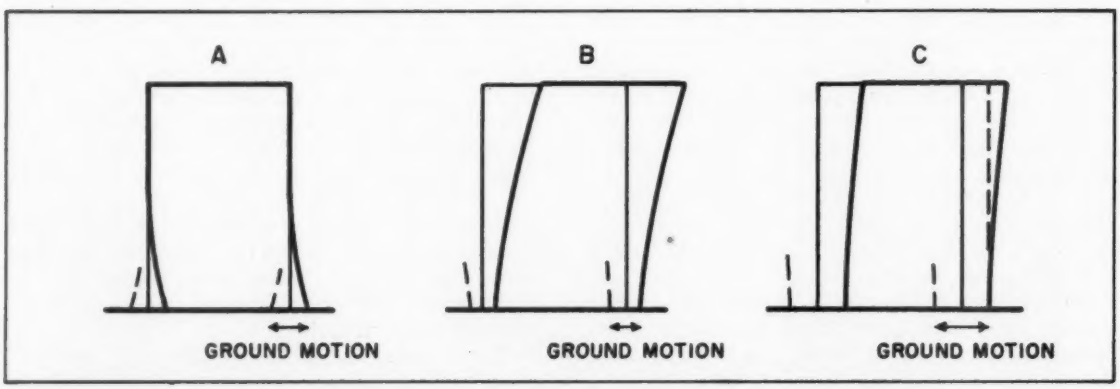

FIG. 3. PRINCIPAL TYPES OF BUILDING DEFORMATION DUE TO GROUND VIBRATIONS

A. Response to high-frequency ground vibrations. Upper part of building remains practically fixed. (Small ground amplitudes)

B. Response to "resonant" ground frequencies. Upper part of building may vibrate through many times the motion of ground.

C. Response to low ground frequencies. Top-floor acceleration is greater than ground. This difference and building deformation decrease with decreasing ground frequency.

usually associated with accelerations so small that it is difficult to find them on acceleration records.

It is acceleration in some form that causes damage. But, while it is acceleration that causes a building to become deformed, and possibly crack up, the deformation itself is measured best in terms of relative displacement between the various floors. A building may be considered as having been damaged by a deformation which could be either dynamic or static in origin. In the past there has been much controversy as to whether acceleration or displacement is the more important element of a vibratory motion to measure. The fact seems to be that both are needed if all aspects of damage are to be adequately considered. It is fortunate that if records are analyzed in terms of simple harmonic motion, simple formulae can be used to convert acceleration to corresponding displacement, or displacement to corresponding acceleration, so long as the vibration period is known.

Because of the high frequency of accelerometer pendulums, they behave like stiff flat springs with one end fixed to an instrument base and the other end free to oscillate except for a damping force that keeps all seismograph pendulums from oscillating in their own free period while recording ground vibrations. Accelerometers are rugged instruments which feature on their records the high-frequency waves that are practically always (in earthquake and blast vibrations) the waves of maximum acceleration and are, perhaps more often than not, very damaging waves. One great advantage of the accelerometer is that the pendulum vibrates almost in unison with the vibrating ground or building except that at the end of each swing the pendulum overswings the motion of the ground. Regardless, therefore, of the amplitude of the ground or building motion, the accelerometer pendulum moves right along with it and thus is capable of measuring indirectly vibratory displacements that would be too great for any "steady-mass" type of displacement seismograph to measure.

In addition to displacement meters and accelerographs there are seismographs of the so-called intermediate type. Although they do not directly measure acceleration, velocity, or displacement of a vibratory motion, from their records the acceleration and displacement of all discernible wave forms can be computed. If the pendulum of such an instrument were highly overdamped, the record would represent the velocity of the motion over a limited range of ground periods. Since maximum velocity is a function of the energy of a vibratory motion, an ideal type of record would seem to be one that measures the damaging potential of a vibratory motion; but, for a number of reasons, such an instrument is not feasible. When the maximum velocity of a vibratory motion is desired, it can easily be computed from either the known period and acceleration, or the period and displacement of the vibration.

Cause of Building Vibration Damage

While damage may always be accompanied by distortion of some kind before a wall or ceiling actually cracks, the writer believes that damage can be divided into two broad categories: (1) damage caused purely by the acceleration or "force" of a vibration, and (2) damage caused by the deformation (shear or flexure) of a structure. The first type involves only the acceleration of the motion which exerts a force on the object being shaken. It is entirely a matter of dynamics. The second type, caused by deformation, could be the result of either a dynamic force or a static force such as that exerted on a structure by a strong steady wind. The distinction seems important in evaluating damage because in one case it is acceleration that causes damage, in the other it is differential displacement or deformation of the structure.

It is quite conceivable that wall and other damage may occur with little or no building deformation. A strong horizontal vibration may throw a kitchen cupboard suspended on hooks clear of the wall; a panel vibration may be set up in a wall or ceiling that will damage plaster; and a parapet wall may be knocked over with but little differential motion between the basement and roof of the building. Such damage would be related directly to the acceleration of the building motion. Even where there is building deformation, the damage on an upper floor could still be due in part to acceleration as well as distortional movements.

When damage is due to shear of flexure in a building, it is important in evaluating a damaging vibration to know what factors control the nature and magnitude of the building deformation. Theoretically a building reacts to a ground vibration in the same manner that a pendulum does. In theory we can visualize an inverted pendulum or oscillator (such as a flat spring with a mass fixed to the free end and the bottom fixed to a base) oscillating back and forth with one degree of freedom in the same manner that a building might oscillate. If the oscillator has the same natural period as the building and the same degree of internal friction or damping, we could say that under the influence of earthquake or blast vibrations the motion of the oscillator would simulate the motion of the center of oscillation of the building. Some of these factors, so far as buildings are concerned, can be only roughly approximated, but even probable values would be of use in estimating the order of building distortion to expect.

The theory covering the motion of such an oscillator when its point of support is subjected to steady-state vibrations is covered in many textbooks on

theoretical mechanics and especially in textbooks on seismology. While neither earthquake nor blast vibrations fulfill exactly the requirement of the steady-state vibration visualized in theory, there is evidence to show that ground waves of different periods are usually propagated in groups of two or more waves, and that in a very short time the oscillator responds as if the ground motion were a steady-state vibration. Quite often the fact that a high-frequency ground wave may be superposed on a low-frequency ground wave is reflected in the theoretical response of the oscillator. It may respond much more to one frequency than to another. The next few paragraphs will show how an oscillator or building may be expected to respond to different frequencies imposed on it by earthquake or blast vibrations.

The curves in Fig. 2 show the relative motion between the center of oscillation of an oscillator (or building) and the moving ground when the oscillator is set into vibration by steady-state ground vibrations of various periods. The amplitude of all ground vibrations is indicated by the ordinate marked 1.0. The ordinates of the various curves show the deflections of the oscillator, or building, for various periods imposed on the oscillator and for various degrees of oscillator or building damping. A damping ratio expresses the amount which an oscillator will overswing its zero position if it is pulled to one side and allowed to come to rest of its own accord. If a pendulum is pulled to one side a distance of one inch and, when released, overswings its initial zero position by ¼ inch, the damping ratio is said to be 4-to-1 or just 4.

The abscissa in Fig. 2 are the ratios between ground and pendulum periods. The left end of the chart shows what happens when high-frequency (short-period) waves are imposed on an oscillator or building which has a considerably longer period. While the ground and building foundation is vibrating through unit amplitude (indicated by 1.0 on the ordinate), the center of oscillation of the building remains practically fixed in space. The relative displacement between the two is therefore virtually the displacement of the ground itself. In an actual building this can be accomplished by a deformation of the general type illustrated in Fig. 3A. For rapid vibrations the building distortion can never differ much from the ground displacement.

When ground and building periods are equal or nearly equal, a state of resonance or near-resonance ensues in which the maximum displacement of the building or oscillator may be several times the displacement of the ground, depending largely upon the amount of friction or damping present in the vibrating unit. This may vary greatly. In one instance a seismograph on the top floor of a tall building registered ten times the motion of the basement instrument during an earthquake originating 200 miles away. Experience shows, however, that a factor of 4 may be considered a representative amplification of top-floor motion over basement motion in average type earthquake vibrations, and there is evidence to show that this may apply to blast vibrations also where resonance or semiresonance is indicated.

There are methods of computing exactly what the maximum deflection of an oscillator will be if subjected to a known earthquake motion, provided the period and the damping of the oscillator are known. However, these procedures are costly. The best way to gain more information on such amplification factors is to mount more seismographs in the basements and on the top floors of buildings. Although the factor 4 was suggested as representing amplification when near resonance exists, this factor may vary greatly in different types of buildings. Figure 3B is intended to show in a simple way the effect of resonant vibrations on a structure. Since the building is always forced to vibrate with a period equal to that of the ground vibration, a four-fold amplification in a top-floor vibration also means a four-fold increase in the acceleration over that experienced in the basement.

It will be noted in Fig. 2 that in going from high-frequency ground vibrations to resonant vibrations the change in the type of building response obtained is not abrupt but gradual. The same is true as one proceeds to study the effect of low-frequency (long-period) waves on a structure. As one moves away from the resonant stage in either direction, the amplification factor 4 theoretically would be decreased by an amount indicated by the ordinates of the curves in Fig. 2. It should also be remembered that these curves indicate amplification of the center of oscillation of a vibrating structure which would ordinarily be at a level considerably greater than half the height of an ordinary building.

When a low-frequency vibration is imposed on an oscillator or building that has a considerably higher natural frequency, a still different type of building reaction is obtained. The building may be said to move back and forth almost in unison with the ground motion, but at the extreme end of each ground vibration the building is found to be overswinging the maximum ground displacement and thereby undergoing a certain degree of deflection or distortion. This is precisely what an accelerometer pendulum does. The amount of this deflection for a given ratio of ground period to pendulum period is shown by the ordinates of the curves on the right side of Fig. 2, remembering that the amplitude of the ground motion is indicated by the ordinate marked 1.0. When the ground period is more than

two or three times the pendulum period, the deflection of the center of oscillation of an oscillator or building comes close to $(T_o/T_e)^2$ times the amplitude of the ground motion, where T_e is the oscillator period and T_o is the ground vibration period. Figure 3C, which presents this type of building deformation diagrammatically, shows that as the ground periods become longer, the building deformation becomes less.

In recent years "earthquake spectra" have been employed to predict the maximum movements that oscillators or buildings of known frequency and damping will experience when subjected to known earthquake motions such as those registered on strong motion seismographs. A spectrum shows the maximum responses of a series of oscillators that cover a wide range of frequencies. Each oscillator response simulates that of a building having similar period and damping characteristics. Earthquake spectra can be computed from the instrumental records of any earthquake, but they differ rather widely in pattern until the damping factors are made quite large. For a damping factor of 0.2, the spectrum (center-of-oscillation) accelerations are from 2 to 4 times greater than the higher ground accelerations, sometimes even more than this. The average amplification is about 2.5 times. This agrees reasonably well with the average amplification factor of 4 previously applied to top-floor motions, remembering that top-floor amplifications would be something less than double the spectrum amplifications. In the spectrum these amplification factors also cover a very wide range of oscillator (building) periods, thereby vitiating to some extent the concept that maximum amplification occurs only at resonant periods, as indicated in Fig. 2. In subsequent discussions of building resonance it would seem, therefore, that the degree of resonance would be unimportant so long as building and ground periods are not too far apart.

While the spectrum represents an approach to the building response problem that is mathematically more precise than a method that depends on the assumption of sustained harmonic motion (as outlined in the preceding discussion of building response), it involves a number of other imponderables, such as wide ranging damping factors and earthquake motions that differ widely in pattern. Hence a simpler method would be desirable.

Crandell's Investigations

The Crandell paper, mentioned in the introductory paragraphs, describes the results of experimental work designed to determine the magnitude of blast vibrations that could be damaging at short distances, the maximum blast distance being only 250 feet. Crandell measured the vibrations with high-frequency oscillators that registered acceleration directly on the record, and his data provide perhaps the best information published to date on the characteristics of high-frequency blast vibrations of damaging magnitude. His criteria for evaluating damaging vibrations were obtained by observing the damaging effect of various ground vibrations on structures and structural parts that were already in a state of stress. The detailed data involved in this study do not appear in the published paper, but, as will be shown, they are consistent in general pattern with the results obtained by the U. S. Bureau of Mines and by the writer in his study of earthquake vibrations.

Within the frequency range of 10 to 60 cps, Crandell found that he could express a damaging vibration in terms of the acceleration and frequency of the vibration. This idea is based on the well known kinetic energy equation K.E.$=\frac{1}{2}mv^2$, in which m may be taken as unit mass and v the maximum velocity of the oscillatory ground vibration. Since velocity, v, is equal to acceleration, a, divided by 2π times the frequency, n,

$$\text{K.E.} = \frac{m}{2} \frac{a^2}{4\pi^2 n^2} = \frac{m}{8\pi^2} \frac{a^2}{n^2}$$

Considering $m/8\pi^2$ a constant, it was found that the damaging capacity of a vibration varied as a^2/n^2. Crandell found that he reached a "caution" zone when a^2n^2 was 3, a being expressed in ft/sec^2. When a^2/n^2 was 6, the vibration was potentially damaging.

Crandell did not attempt to estimate the ground motion at a given distance for a given weight of explosive (as described, for instance, in Bureau of Mines Bulletin 442, Table 6), but in each case fired a small shot that enabled him to determine the particular vibration characteristic of the ground or rock under investigation and thus determine the weight of explosive that would keep a^2/n^2 below 3, the lower limit of the caution zone.

Crandell also determined what vibrations in the 10- to 60-cps frequency range were considered by people to be severe, troublesome, and noticeable. These data are particularly valuable in showing how the sensations of uninformed persons can be entirely misleading in attempting to evaluate the damaging power of vibrations they experience. Moreover, such data make it possible to compare these vibrations with lower frequency earthquake vibrations in which similar effects on people are reported.

Bureau of Mines Investigations

Bulletin 442, previously mentioned, summarizes in considerable detail the result of operations described in a series of Bureau of Mines "Professional

Papers" issued at intervals over a ten-year period. Perhaps the most valuable result of this investigation was the preparation of a table showing the amplitudes of ground motion to be expected from various weights of explosives (from 10 to 10,000 lb) at various distances (from 100 to 6000 ft) on different types of soils and rocks. While this table provides only a rough estimate of the ground motion to expect and in itself embraces a wide range of uncertainty, it nevertheless provides valuable preliminary information as to whether or not a given weight of explosive, at a specific distance, on a known type of soil or rock, would come even within range of being potentially damaging. This would depend to some extent, of course, upon what criteria one used to define a damaging ground vibration, but such criteria also are subject to limitations.

The weakness of the Bureau of Mines' work, insofar as evaluating damaging vibrations was concerned, lay primarily in the inability of the investigators to find any residential damage that could be attributed without qualification to blasting operations. The extremely few cases in which damage was observed could hardly be considered sufficient for drawing definite conclusions, and in the large number of cases in which damage was inflicted by a shaking machine, a serious question arises as to how to interpret such results in terms of damaging ground vibrations.

"Earthquake Intensity and Related Ground Motion"

In 1932, the U. S. Coast and Geodetic Survey installed its first strong-motion seismographs in California in a program designed to furnish structural and foundation engineers with basic data on damaging earthquake vibrations, thus enabling them to evaluate earthquake stresses in buildings and other structures. A valuable part of this program has been the collection of descriptive reports relating to the effects of earthquake vibrations on people and inanimate objects throughout shaken areas. The instrumental data and descriptive reports thus collected are published in a number of seismological bulletins issued periodically by the Survey and summarized in annual publications of the "United States Earthquakes" series. Unlike the Bureau of Mines, the Survey has issued no official report which either in whole or in part attempts to define a damaging earthquake vibration, even though the type of data collected affords this opportunity.

It was not until 1950 that the writer, then chief seismologist in the Survey, found opportunity to undertake a study of at least a portion of the mass of instrumental and non-instrumental data collected over nearly a 20-year period and to evaluate earthquake ground motions in terms of their effect on structures. In 1953 the writer retired from the Federal service to take over the seismological activities of the University of Washington, and in 1954 the University of Washington Press published the results of these investigations under the title "Earthquake Intensity and Related Ground Motion." In this booklet of 100 pages, which must be considered a highly condensed version of the research and its results, no attempt was made to compare damaging earthquake motions with those reported by other investigators.

Using the Modified Mercalli Intensity Scale of 1931 as a base to work on, the writer used the data obtained from the Survey's strong-motion seismographs (mostly accelerographs) to determine what ground accelerations were applicable to the various grades of the intensity scale. Since Grades V and VI of this scale indicate a violence of motion that begins to cause damage, it followed that the maximum ground acceleration associated with these particular grades could be designated potentially damaging motion. In this work the maximum accelerations are associated with an average frequency of 3 cps and are limited to epicentral areas. This tentative assumption cannot be extended over too wide a range without introducing discrepancies in the intensity-acceleration relationship.

In the Modified Mercalli Scale superficial damage is first mentioned in Grade V in which buildings tremble throughout, dishes and glassware are broken to some extent, some windows are cracked, vases and small or unstable objects are overturned in many instances and sometimes fall, etc. If a town housing thousands of people reports any one of these happenings, the intensity is designated Grade V in Coast and Geodetic Survey reports even though a portion of the population might not even know an earthquake had occurred. It is important to know that these intensity designations always represent the worst effect reported in a community and, most of the time, represent damage to the most poorly constructed homes on unconsolidated or loose ground. Damage to dwellings is always greater on loose soil than on well-consolidated soil or rock. It would be a mistake to believe that in a Grade V earthquake motion the effects listed in the intensity scale are supposed to occur on a broad scale unless so stated. Intensity V means that these things could happen if all of the conditions are favorable. In the study of Coast and Geodetic Survey data the writer has associated Grade V intensity with an average acceleration of 0.032 g associated with a frequency of 3 cps.

For Intensity VI the Scale states the following possibilities regarding damage: damage slight in poorly built buildings; fall of plaster in small

(Continued on page 24)

BIOCHEMICAL DEGRADATION BY-PRODUCTS: A NEW FORM OF WATER POLLUTION?

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R. H. Bogan

The primary objective of most water-pollution control programs is to realize the maximum beneficial use of our natural water resources. The beneficial uses to which a water may be put are many and varied, ranging from human consumption to waste disposal. Pollution-control programs at the practical level normally take the form of a number of water quality standards or criteria which must be satisfied. These standards usually describe the tolerance limits for various physical, chemical, and biological constituents and properties. Water quality standards are generally considered to be clear cut and definitive.

Unfortunately it has not been possible always to describe all facets of stream pollution in unique or precise terms. Stream-pollution standards as they have developed are an interesting mixture of rigorous limits of an exact nature on the one hand and broad generalized requirements on the other. For example it has become common practice to prescribe limits for biochemical oxygen demand, tastes and odors, etc., with the same sense of reality and confidence as with dissolved oxygen, pH, and various chemicals such as cyanides and chromium. There appears to be no middle ground. What escapes the dragnet of conventional concepts and analyses does not exist!

During recent years there has been an increased interest in the fate of synthetic organic chemicals reaching the nation's surface waters. Reports of wastes containing organic compounds which are resistant to biological breakdown and the finding[1] of numerous organic substances in domestic water supplies raises some interesting questions concerning stream-pollution criteria.

The purpose of this paper is to examine some of our currently accepted practices of measuring stream pollution in the light of recent changes in the nature of the materials reaching our surface waters. Reports of the findings of others will be drawn upon. The results of research conducted by the writer will be presented.

THEORETICAL CONSIDERATIONS

Means of Measuring Biochemical Pollution Loads

When naturally occurring organic compounds such as fats, carbohydrates, and proteins are introduced into a natural body of water they are immediately set upon by its plant and animal life. During the ensuing course of biological attack the organic compounds are broken down to liberate energy, mineral residues, and new cell material. While such phenomena may follow complicated pathways on the way to completion, the general reaction involved in the biochemical oxidation of waste organic materials may be very simply summarized as follows:

$$\text{Organic Material} + \text{Microorganisms} + O_2 \longrightarrow \underset{\text{C-H-O-N-S-P}}{}$$

$$CO_2 + H_2O + \underset{\text{C-H-O-N-S-P}}{\text{New Cell Tissue}} + \text{Energy} + \underset{\text{C-H-O-N-S-P}}{\text{By-Products}}$$

The fact that oxygen is consumed during such a reaction, is of considerable practical significance from the standpoint of stream-pollution control. Because all receiving waters have a limited supply of oxygen available at any given time, such biochemical reactions may have serious consequences. If such a reaction were to take place at a sufficiently rapid rate the oxygen content of the water may become depleted. Under such conditions the water cannot support desirable fish life. It may even turn anaerobic and produce obnoxious tastes and odors. Such happenings are not mere theoretical conjecture but constitute a very real problem. Obviously, then, the organic properties of a waste which result in this biochemical consumption of dissolved oxygen are a very important factor in most stream-pollution control programs. Tests aimed at measuring the biochemical oxygen demand of a waste or of a receiving water are indispensable tools to pollution-control authorities.

Many years of research and experience in the development of our present-day methods of measuring biochemical pollution have resulted in the two general approaches used today. One attempts to measure the actual rate and amount of biological oxygen consumption. The other attempts to measure the chemical reactivity of the waste constituents in terms of the theoretical amount of oxygen required for complete combustion. The first type is known as the biochemical oxygen demand test or simply

the B.O.D. test. In this procedure the waste or water under investigation is placed in an air-tight bottle and incubated for a given period of time at a specific temperature (normally 5 days at 20° C) and the resulting oxygen depletion due to biochemical oxidation is measured. The second type of approach is known as the chemical oxygen demand test or, more commonly, the C.O.D. test. In this technique the substance being studied is simply placed in contact with some strong oxidizing chemicals and the amount of oxidizing reagent required to burn up the material is expressed in terms of gaseous oxygen. Both methods are aimed at measuring one thing, namely, the amount of oxygen required to stabilize the organic materials present in a waste or polluted body of water.

Limitations of B.O.D. and C.O.D. Measurements

The use of biochemical and chemical oxidative procedures as a measure of organic pollution has become common practice. The generally accepted practical interpretation of such information is that the greater the oxygen demand the greater the degree of pollutional strength, other things being equal. Experience tends to substantiate this line of reasoning. On the other hand, theoretical interpretations of such data have not enjoyed such unanimity of opinion or of experience.

One of the most serious theoretical misinterpretations stems from attempts to explain events taking place during the course of the B.O.D. reaction by monomolecular reaction kinetics. While the simple expression,

$$\frac{dL}{dt} = -KL,$$

has found widespread practical use, it does not follow that the biochemical conversion of organics behaves in this manner. The analogy between ultimate biochemical oxygen demand, L, and organic food material has led many to an erroneous concept. It has become common to consider the residual B.O.D. at any time as due to an unused portion of the original food material. In other words, the B.O.D. reaction proceeds by assimilation of whole molecules of the original organic material. Thus one molecule of food is converted to CO_2, H_2O, or cell tissue before the next is used. In the case of readily assimilated substances, such as simple sugars, something approaching this appears to take place. With more complex organics, evidence points to a different process.

Attempts to correlate B.O.D. and C.O.D. values are a good example of the inadequacy of the concept of whole molecular conversion. If the B.O.D. reaction is as described by the monomolecular reaction equation, then it should be possible to calculate B.O.D. values from C.O.D. data or vice versa. With a few exceptions this has not been possible. Obviously more is involved than a straightforward molecule-by-molecule destruction. Actually, considerable evidence, both in nature and from practice, indicates that the so-called B.O.D. reaction is a complex step-wise procedure. While it is entirely possible that many simple substances can be completely assimiliated by one species of microorganism, it is equally probable that many organics are destroyed in a series of symbiotic steps or processes. Termination or interruption of a symbiotic type of relationship would result in the production or accumulation of partially degraded by-products. Many such events have been recognized in nature. In fact whole industries have been built on the use of biochemical production of organics such as antibiotics, etc. The possibility of such events occurring in biological treatment units and in receiving waters should not be overlooked.

B.O.D. and C.O.D. data are of considerable value in determining the oxygen requirements for disposing of a waste. Such data by their very nature tell little of the events leading up to the point at which oxygen utilization values are measured. Information obtained from these tests does not describe the qualitative nature of the residual or unreacted materials which may be present.

During a study of the biochemical oxidation of a number of pure organic compounds evidence was obtained which indicated that biochemical degradation products might be formed from certain classes of compounds. Attempts were made to gain more information about this situation. Several experiments were conducted aimed at determining the nature of the suspected biochemical end products. The results of these experiments are reported in the following section.

EXPERIMENTAL RESULTS

Materials Studied

The data reported on here were obtained by the writer during an investigation of the biochemical behavior of synthetic organic detergents. A number of related organics were studied in addition to the different types of detergent molecules. Included in the materials studied were alkanes, high molecular weight fatty acids and alcohols, low molecular weight ethylene glycols, and a number of alkyl benzenes. The list of substances studied has been discussed in more detail elsewhere.[2,3,4]

Experimental Procedure

The method of study was to develop activated sludges (mixed biological cultures) for each substance and subsequently to measure the ability of these cultures to biochemically oxidize the compounds under investigation. The exact experimental procedure has been described earlier in detail.[2,3] In

TABLE I

PROBABLE RELATIVE ENZYME REACTION RATES IN ACCLIMATED ACTIVATED SLUDGE

REACTION	REACTION SITE	RELATIVE RATE*
Hydrolysis		
$R\text{–}SO_4Na \xrightarrow{+H_2O} R\text{–}OH + NaHSO_4$	Alkyl sulfate	100
$RCON(R')(R'') \xrightarrow{+H_2O} RCOOH + HNR'R''$	Sulfonated amide	100
$RCOOR' \xrightarrow{+H_2O} RCOOH + R'\text{–}OH$	Sulfonated ester	100
Fission		
Unsaturated aliphatic	Oleate	88–96
Benzene ring	Benzene	22
Terminal and ω Oxidation		
$RC\text{–}OH \xrightarrow{1/2\ O_2} RCOOH$	Aliphatic alcohol	67–100
$R\text{–}H_2C\text{–}CH_3 \xrightarrow{3/2\ O_2} R\text{–}H_2C\text{–}COOH$	Aliphatic terminal	37
	Aromatic alkyl terminal	33–38
	Aromatic alkyl side groups	10–33
β Oxidation		
Aliphatic carbon chain	*n*–alkyl benzene SO_3H	100
$R\text{–}CH_2\text{–}CH_2\text{–}COOH \xrightarrow{O_2} R\text{–}COOH + CH_3COOH$	Stearate	100
	n–aliphatic alcohol	100
Ether linkage	Ethoxy polyglycols	67–83

* Oxygen utilization for β oxidation in saturated aliphatic acid chosen as basis of comparison.

addition to these biochemical oxidation determinations, cell-free extracts were taken after an extended period of oxidation and analyzed for their organic residues by infrared spectroscopy.

Biochemical Reactions

It is generally recognized that the assimilation of an organic compound by living cell tissue involves a number of enzymatic changes or steps, the exact number and types of enzyme-induced steps being dependent upon the nature or chemical structure of the food substance involved.[5,6] A number of commonly occurring enzyme reactions have been recognized.[6] Most notable of these from the standpoint of waste treatment are hydrolysis, fission or rupture of ring structures and unsaturated aliphatic chains, β oxidation or degradation of aliphatics, and ω, or terminal, oxidation of saturated endings on carbon chains. In other words these are the means by which complicated compounds may be broken up into simpler pieces and the manner in which organic materials are combusted biologically.

The biochemical oxidation reactions observed during the investigation[2,3] have been re-examined in terms of the probable major enzyme reactions involved. Apparent reaction rates during the first 30 to 60 minutes were taken as a basis for analysis and comparison. During the early stages of most of the biochemical reactions, the original food molecules should be involved. At subsequent times the situation is more obscure.

The relative rates at which certain reactions appeared to take place have been recorded in Table I.

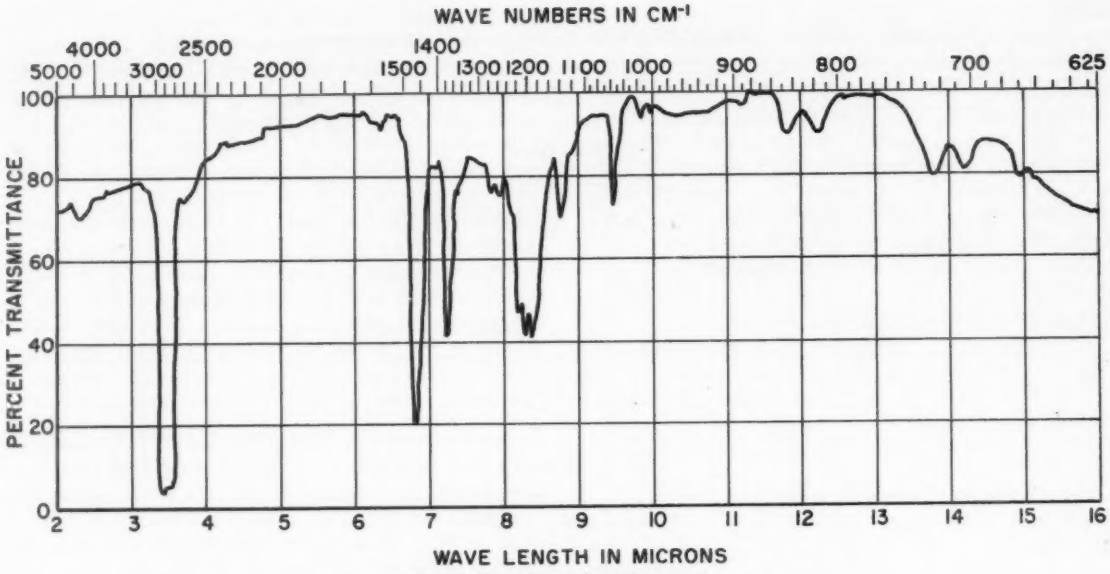

FIG. 1. INFRARED SPECTROGRAM
Nujol mull *n*-dodecyl ΦSO_3Na pure chemical identity

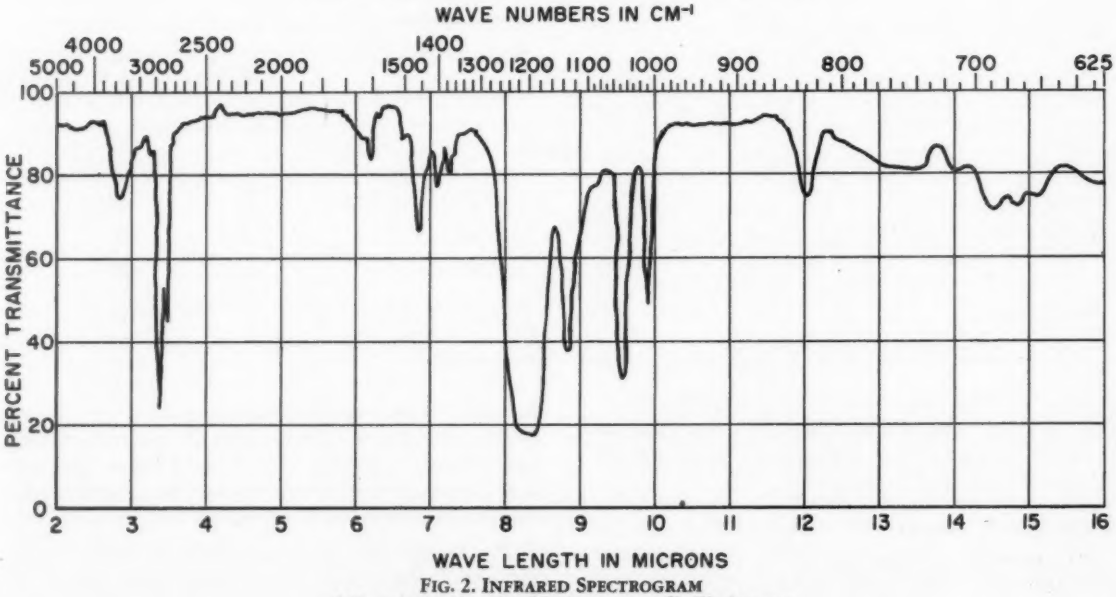

FIG. 2. INFRARED SPECTROGRAM
CCL_4 solution keryl ΦSO_3Na narrow distillation cut

These rates are based on the oxygen utilized during the breakdown of each organic compound when it was the only source of food available to the microorganisms present in the culture. The apparent rate of conversion of stearic acid by β oxidation was taken as the basis for comparison. These values may be somewhat problematical. They merely summarize the results observed during this investigation.

As previously noted, many enzyme reactions may be involved in the sequence of events leading to the degradation of an organic compound. The kinetics of complex multireaction systems have often been characterized by one rate-controlling reaction. The data presented in Table I indicate that certain reactions may act as bottlenecks, so to speak. For example, in the case of the alkyl benzene sulfonates, they

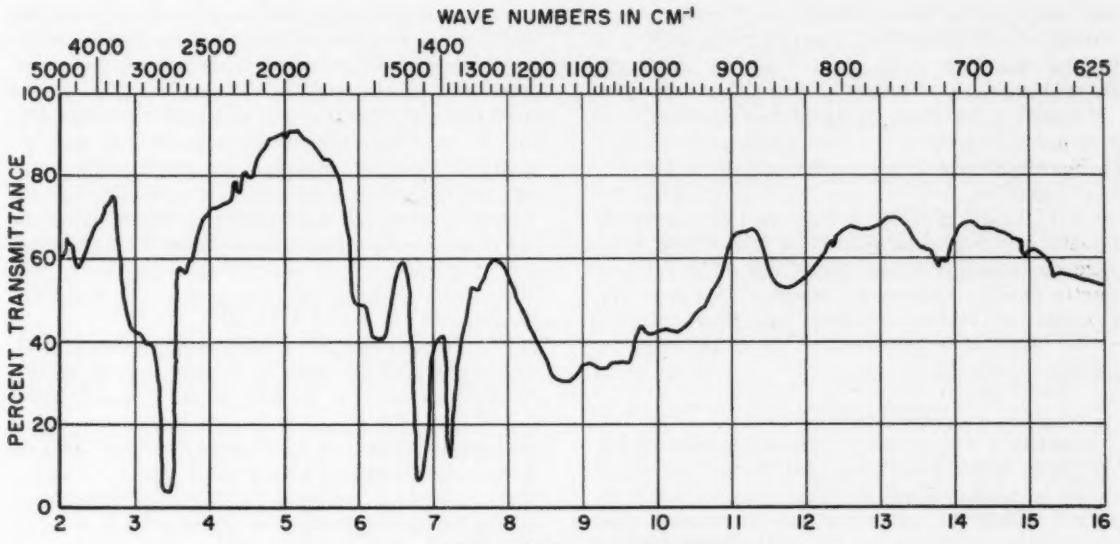

FIG. 3. INFRARED SPECTROGRAM
Nujol mull *n*-dodecyl ΦSO_3Na biochemical oxidation products

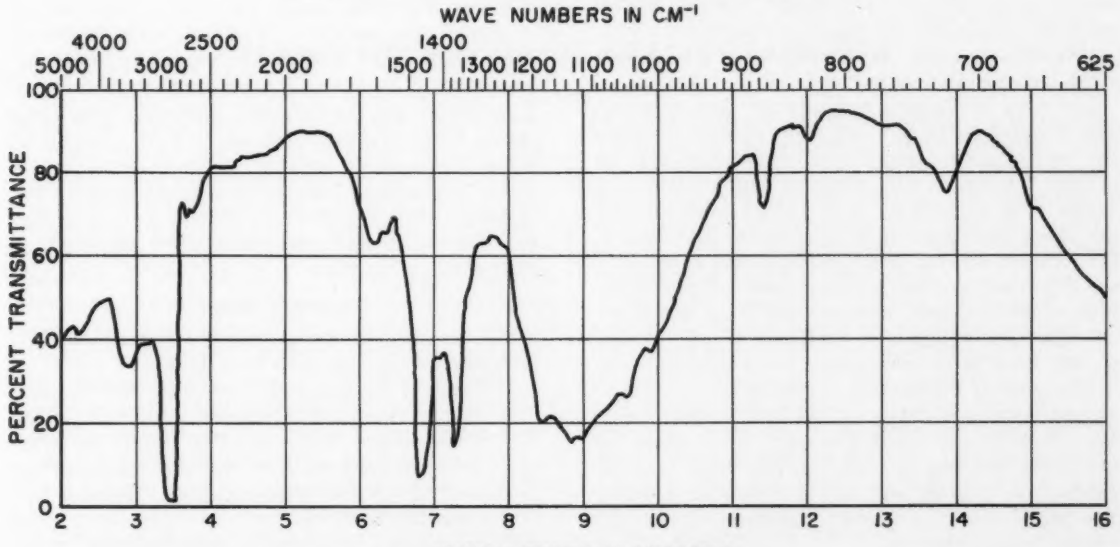

FIG. 4. INFRARED SPECTROGRAM
Nujol mull keryl ΦSO_3Na biochemical oxidation products

indicate that difficulties may be encountered in both the alkyl group and in fissioning the benzene ring. If such events do take place then one would expect to find some evidence of it in the form of biological degradation products. In order to check this hypothesis, material was withdrawn from activated sludge systems and analyzed for the presence of postulated by-products.

Infrared spectrograms are shown in Figs. 1 through 4 for two of the alkyl benzene sulfonates studied. One of these materials was pure para-*n*-dodecyl benzene sulfonate obtained from the Atlantic Refinery Company. The other substance was a narrow distillation cut of commercial keryl benzene sulfonate, furnished by the Proctor and Gamble Company. Spectra are shown of the original material and of the material remaining after 24 hours contact with acclimated activated sludge. Each substance

was employed as the sole source of organic carbon. Sludge in an endogenous state of respiration was washed with tap water before use to elude any residual organics.

Inspection of these spectrograms discloses the presence of numerous oxidized aromatic derivatives of the original organics. Absorption spectra for aromatic alcohols, ketones, aldehydes, and acids are present.[7] Data in Table I indicate that a benzene nucleus might tend to restrict or slow down complete degradation of such molecules. The infrared spectra tend to confirm this concept. Interestingly, a somewhat similar situation has been observed in the case of assimilation of alkyl benzenes by animals.[8,9]

DISCUSSION

Experience with persistent organic substances has led many to the conclusion that stream pollutants cannot be evaluated satisfactorily in terms of B.O.D. alone.[10] Because biochemical oxidation can create real and serious problems, tests aimed at assessing oxygen requirements have a practical meaning and value. Few will argue with the importance of B.O.D. data as a measure of a significant form of stream pollution. However, the question should be asked: Is this the only aspect of biochemical pollution with which we should be concerned?

The work of Ettinger,[10] Ludzack,[11] and Sawyer,[4] calls attention to the fact that many types of organics may persist in receiving waters for extended periods of time. Obviously any material that persists in a stream is as important, until proved otherwise, as one which undergoes rapid biochemical degradation. This concept has led to the rather broad generalization that there are two general classes of materials: those which are easily oxidized and those which are not. Pursuing this line of reasoning a little further has led some to the conclusion that compounds exhibiting ease of biochemical oxidation are of no consequence except in terms of dissolved oxygen depletion. Both Cairns[12] and Ettinger[10] have raised an interesting question in regard to this latter concept, namely, are organic end products produced which may be of equal or greater significance than the original waste materials?

Cairns[12] points out that little attention has been given to the effects of the compounds formed by attenuation of wastes after they enter the stream. He adds, moreover, that at times these secondary compounds are more toxic than the originals. Ettinger[10] has recognized that both new cell tissue as well as soluble metabolic end products may cause a residual B.O.D. long after the original chemical is gone.

It should be recognized that an apparent termination of the so-called B.O.D. reaction is not evidence in all cases that the original food material has been converted to cell tissue, CO_2, and water. The B.O.D. test is a relative one. The rate and extent to which organics are oxidized are dependent upon the microorganisms present and the chemical structure of the food material. Even under carefully controlled laboratory conditions the course of the B.O.D. reaction may be difficult to interpret.[13] As McKinney[14] points out, as long as a compound fits into the common metabolic pattern, the metabolism is rapid. Once the chemical structure causes a deviation from the common pattern, it is broken down very slowly and with much difficulty on the part of the microorganisms.

The findings of this research indicate that B.O.D. values observed for many substances may be related to degradation of a portion of the molecule only. In the case of the alkyl benzene sulfonates described in this paper, much of the oxidation observed appears to have been centered in the alkyl groups. A somewhat analogous situation has been described by Ludzack[11] during a study of the biochemical oxidation of oils. He was able to identify the presence of oxidized alkane derivatives by the use of infrared spectroscopy. It does not always follow that biochemical oxidation would continue to be centered in the original molecule. Through such operations as hydrolysis and fission the original organic may be converted into two or more fragments. Some of these derivatives may be easily oxidized; others may persist for considerable periods of time. Conditions below many waste outfalls might be described in terms of a unique fractionating mechanism, with biochemical oxidation products extending downstream in relation to their persistence and sequence of formation.

CONCLUSIONS

On the basis of the foregoing considerations the following conclusions have been drawn.

1. Organic stream pollutants may not be adequately evaluated in terms of B.O.D. or C.O.D. values alone. Nothing in the B.O.D. test provides for description of residual organics which may be present after varying periods of biochemical oxidation.
2. Biochemical degradation intermediates or by-products have been demonstrated during the breakdown of oils and alkyl benzene sulfonates. The possibility of their production from a number of other sources exists.
3. Oxidation of an organic may be related to only a portion of the original molecule. Through hydrolysis and fission a substance may be broken into two or more fragments. It is entirely possible that certain fragments may be relatively resistant to oxidation, whereas others may be rapidly oxidized.

4. Many consecutive enzyme reactions may be involved in the degradation of an organic. Some of these reactions have been found to occur at much slower rates than others. Evidence has been found which indicates that certain enzyme reactions, such as fissioning of the benzene ring, may regulate the rate at which a substance can be oxidized. Biochemical degradation products may be caused to accumulate at such reaction points.

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University's Nuclear Reactor Installed

The College of Engineering's new sub-critical nuclear reactor, the first of its kind to be installed on a university campus, has been set up and tested in Bagley Hall. On page 2 a view of part of the equipment appears, with Dr. A. L. Babb, who is in charge of the Nuclear Engineering Laboratory (*in white coat*), Dr. R. W. Moulton, head of the Chemical Engineering Department (*left*), and Dean Harold E. Wessman of the College of Engineering. Dr. Babb is demonstrating how a plutonium-beryllium neutron source is inserted in a removable graphite stringer.

The reactor is a miniature of the giant plutonium-producing piles at the Hanford Atomic Works, and is designed for training purposes. It is capable of producing a chain reaction but not on a self-sustaining basis. It consists of 8 tons of graphite blocks forming a 5½-ft cube pierced by "cooling channels" filled with aluminum-jacketed uranium slugs. The cube rests on a pedestal consisting of 7 tons of graphite. About 2½ tons of uranium, on loan from the Hanford works, are available as fuel.

The reactor and electrical instruments, valued at $30,000, were procured through the A.E.C. grant of $109,000 to the University to expand facilities in the field of nuclear engineering education. The program, which has been under consideration for several years, is broad in scope. Besides the Laboratory which will afford demonstration of the fundamentals of neutron physics and the measurement of constants important in reactor design, the grant will supply monitoring and testing facilities in sanitary engineering, provide special furnaces and equipment in metallurgical engineering, and instruments for detection and study of properties of high level nuclear radiations in electrical engineering.

Dr. Babb, Associate Professor of Chemical Engineering, spent the last three summers studying nuclear reactor operations at Hanford and the A.E.C. Argonne Laboratory. He is assisted by Lars Grimsrud, mechanical engineer; Albert Wakefield, in charge of electronic instruments; and graduate students, Luis Oh, William Wilson, and Thomas Rehm.

Other professors who have been receiving special training in the field of nuclear engineering are Dr. R. W. Moulton and Dr. L. N. Johanson, Chemical Engineering, Dr. R. H. Bogan, Sanitary Engineering, and Professors J. C. Firey and P. J. Waibler, and Dr. M. E. Childs, Mechanical Engineering.

The course of study, which is one of the first established in the West to lead to the degree of M.S. in the field of nuclear engineering, is administered by the Nuclear Engineering Committee consisting of the executive officers of the departments of Chemical, Civil, Electrical, Mechanical, and Mineral Engineering, and Dr. Babb, with Dr. R. W. Moulton as chairman.

Effects of Thermal Upsetting in 5052 Aluminum Alloy*

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R. E. Holt

The problem of distortion and residual stress as a result of nonuniform heating experienced in brazing, welding, and heat treatment of metals is a serious one to design and production engineers. The difficulties stem from locally heating a small volume of a large mass of rigid metal which confines the thermally expanding portion of the structure. Joseph Holt put this phenomenon to practical use as early as 1920 to produce desired bending in structural bridge sections.[1,2]

The present investigation was undertaken to observe and record in a usable form the changes in structure, as well as the plastic and elastic behavior, of a structural alloy confined axially during heating to various elevated temperatures. The writers hoped (1) to develop a confining device to simulate rigid confinement of a heated volume, (2) to gather data to show how the thermal expansion behavior varied, and (3) to determine the influence of prior cold work on the upsetting behavior of axially confined expansion.

Several physical factors are involved in studying restrained thermal expansion. Metals increase in volume with increasing temperature at a rate that may be determined by means of a dilatometric study in which the change in length is measured as a function of the temperature rise. Other factors may be superimposed upon the simple expansion change due to heating. Reactions such as recovery, recrystallization, tempering, and precipitation of more stable phases will also produce volume changes with the magnitude and sign dependent upon the alloy involved. A decrease in yield strength and modulus of elasticity is also generally experienced with this increase in temperature.

J. W. Anderson

To experimentally duplicate localized heating, a short column of metal is placed between fixed faces of an infinitely rigid confining structure. When this column is heated to some elevated temperature, the linear expansion produces a strain due to the end loading from the fixed faces. At first this strain is only elastic—until the proportional or elastic limit is exceeded. All further linear expansion then produces plastic flow with the elastic strain retained at any given temperature equal to the elastic stress divided by the modulus of elasticity for this temperature. Thus, if the metal column is heated to a known temperature under these conditions and cooled to the original ambient temperature, the difference in length from the original is the amount of plastic deformation produced.

E. C. Roberts

A simple device was developed to hold a sample of metal one inch long between parallel faces which would remain a constant distance apart over a considerable temperature range. The device shown in Fig. 1 was accurate from 70° to 850° F. The main frame was fabricated from ASTM A7-49 and the center column from AISI Type 309 steel. This pair of alloys have such thermal expansion coefficients that the Type 309 steel column has the same total expansion as the assembly frame although it is one inch shorter, thus giving the necessary fixed faces.

Aluminum alloy 5052 was used for this investigation since it has a large thermal expansion, low elastic limit, no coherent precipitates, and is not subject to grain growth at elevated temperatures. Specimens one inch long were machined from cold-drawn wire 0.250 inches in diameter. Tests were run with this alloy in the as received H34 (cold-worked) and O (annealed) conditions. The O condition was obtained by annealing cold-worked metal at 850° F for 80 minutes. Two or more specimens were tested at each temperature level in 50°F increments from 250° to 800° F. Additional runs were made at smaller increments at points of inflection of the deformation and hardness curves. Before it was

* A condensation of Professor Holt's thesis submitted in partial fulfillment of requirements for the degree of M.S. in Metallurgical Engineering, 1957, together with the results of certain extended work carried on by Mr. Anderson.

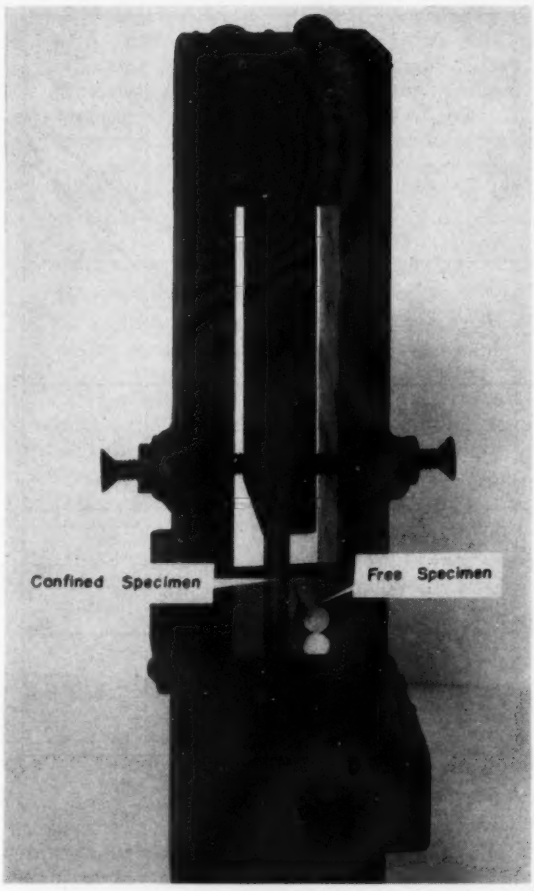

FIG. 1. CONFINING ASSEMBLY FOR THERMAL TESTS

placed in the confining assembly, the sample length was carefully measured at 70° F with a Pratt and Whitney Supermicrometer, M-1471, measuring directly to 1/10,000 of an inch. This known length specimen was then placed in the confining assembly and the wedges tightened by screwing in on the bolt actuating the movable wedge until the specimen could just be rotated with the fingers. This adjustment was critical since it determined the preload on the sample, but was only as accurate as the touch of the operator. Only enough load was applied to insure proper fit-up of the assembly components.

A duplicate sample was placed in a nonconfining position in the assembly for each run to permit a comparison of the microstructural and hardness differences resulting after both thermal upsetting and free expansion. The entire confining device with the confined and free specimens properly positioned, was first placed in an electric furnace preheated to 200° F and then heated to the desired temperature at the approximate rate of 5° F per minute. Temperature of the confined sample was obtained from a chromel-alumel thermocouple imbedded in a small copper clip snapped on the specimen. Owing to the high thermal conductivity and low absorption of the aluminum alloy, the sample remained at very nearly the same temperature as the massive assembly during heating period. The recorded temperature was maintained for 15 minutes before the assembly was removed from the furnace and allowed to cool in still air. When the assembly reached room temperature, the specimen subjected to the restraint during heating was measured and the data logged. These data are plotted in Fig. 2, Curve I. The free thermal expansion curve (II) was plotted from dilatometric studies of the alloy tested. Since no difference was observed between the O and H34 conditions, the curve is valid for both. The theoretical permanent deformation (Curve III) was calculated from data in ALCOA Aluminum Handbook[3] and a private communication[4] and may not be considered exact for the alloy tested but only indicative of the general behavior to be expected. The data for the experimental permanent deformation of the 5052-H34 were taken from a thesis study[5] and those for the 5052-O (Curve IV) from unpublished research.[6]

The two experimental curves (I and IV) may be analyzed from several points of view. The interests of the physical metallurgist and solid-state physicist will be discussed first. The permanent deformation experienced at a lower temperature in the cold-drawn specimens than in the annealed specimens is due to the Bauschinger effect caused by the reversal of prior cold-work and results in a reduced yield strength. Initiation of plastic flow was observed at 250° F for the H34 condition and 310° F for the O condition. The discrepancy between the two curves up to about 400° F is due to the above effect plus a more rapid recovery in the case of the H34 condition. Indications of the latter effect were revealed by a hardness study not reported here. The curves remain similar from 400°F to 650° F where a sharp break occurs in the H34 curve. This level portion seems to be due to an increase in density caused by increased drive for imperfection removal during the recrystallization of this previously cold-worked material. Other authors report findings to substantiate this view.[7,8] The slope of both curves begins to increase rapidly above 750° F. Further study is required here, but apparently the compressibility increases, resulting in increased thermal coefficient of expansion over that revealed from standard dilatometric studies. The simplified Grüneisen equation $B \propto KC$ is the basis for this interpretation, where B is the linear expansion coefficient, K the compressibility, and C temperature-insensitive constants.

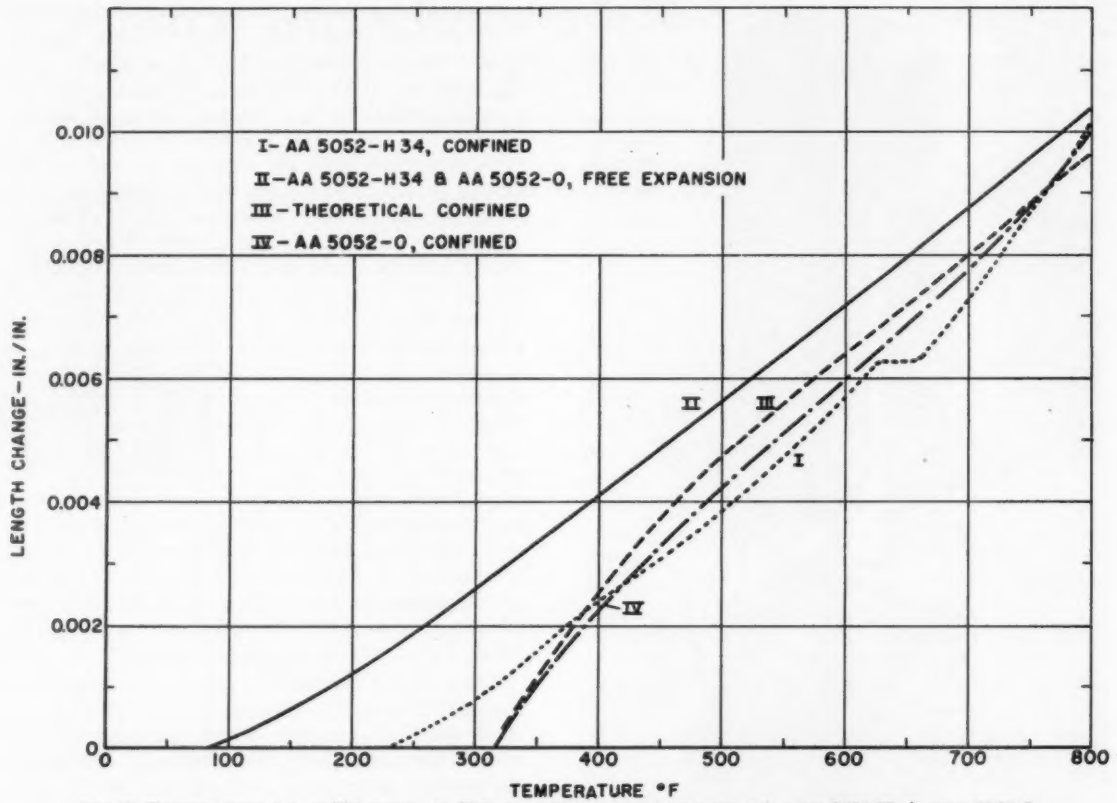

FIG. 2. EXPERIMENTAL AND THEORETICAL THERMAL UPSET OF ALUMINUM ALLOY 5052-H34 AND 5052-O.

The engineer may derive considerable information from the curves in Fig. 2. Fairly good approximation of actual behavior may be made by calculating the theoretical deformation. The data required are the variation of the elastic limit, modulus of elasticity, and linear expansion with temperature. However, not all of this information is available in the literature on deformation behavior.

From the experimental curves, the temperature difference for the initiation of plastic flow may be determined for any ambient from 70° F to 735° F. This information is valuable in setting safe heating or cooling rates for processes involving thermal cycles. To determine the temperature where plastic flow will start, we must (1) find the ambient temperature intercept on the free expansion curve, (2) move horizontally from this intercept to the experimental deformation curve (confined sample). The abscissa difference of these two points is the maximum temperature discrepancy without experiencing plastic flow. ***Examples*** (H34 condition):

AMBIENT TEMP.	TEMP. DIFFERENCE
300° F	115° F
450° F	107° F
750° F	12° F

It is notable that at high ambient temperatures, such as in brazing, very close temperature homogeneity is mandatory for minimum warpage.

The value of the proportional limit strain for any temperature in the range shown may be obtained by taking the ordinate difference between the free thermal expansion and confined thermal expansion curves. Thus, if the proportional limits as a function of temperature were carefully determined, the static compression modulus of elasticity could readily be calculated from such data, with $E=\sigma/\delta$.

The following conclusions may be drawn from this study.

1. Recovery in cold-drawn 5052-H34 aluminum alloy occurs at lower temperatures, takes place at a greater rate, and is more complete when a compression load equal to the elastic limit is imposed uniaxially in the drawing direction.
2. The density of cold-drawn 5052-H34 aluminum alloy increases sharply during the final stages of recrystallization when elastic limit compression is imposed unaxially. This density change is not present in the annealed condition.

3. The compressibility and linear thermal expansion coefficient seem to increase more rapidly when the 5052 aluminum alloy is under elastic limit compression in the grain-growth temperature range than when it is expanded freely.
4. Useful engineering information may be derived from permanent deformation studies of structural materials confined in such a manner as to simulate the conditions of restrained thermal expansion resulting from unequal heating of rigid structures. More attention must be focused on the effects of temperature gradients in thermal cycle processes if engineers are to utilize such methods with reasonable control.
5. More extensive investigation has indicated that recrystallization in cold-drawn 5052-H34 aluminum alloy appears to begin at lower temperatures, grows from fewer nuclei and proceeds more slowly if thermal expansion induced compression is applied in the drawing axis. A more careful and extensive study of these observations should produce some valuable data concerning the effect of pressure on the recrystallization reaction.

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The writers wish to express their thanks to Mr. W. R. Manahan of the ALCOA Seattle Sales Office for supplying the alloy used in this investigation.

OUTSIDE U. S. A.

Highlights from Our Foreign Exchange Publications

Study of Shallow Foundations. R. L. Hermivier, *Annales de l'Institut Technique du Batiment et des Travaux Publics,* Jan., 1957. French.

An examination is made of the rupture resistance of a semi-infinite homogeneous layer either cohesionless or coherent with or without internal friction. The bearing value of a two-layer system is then examined. After studying the limit-bearing value of these layers, there is an examination of the distribution of pressures under a shallow footing, loading the soil not to the point of rupture but to an admissible working load.

The Application of "Rilsan" in Electricity. R. Dumon (Trans. from French; *Ind. Plast Mod.*) *Engg. Dig.,* June, 1957. English.

Rilsan is a French thermal plastic, a superpolyamide produced from the Ricin plant which is grown in French Africa, South America, India, etc. The Ricin oil, which has a 90% of ricinoleique esters content, is subjected to a number of chemical treatments and thermal cracking, and in the end a chemically pure product, the amino-undecanioque acid, is obtained. Rilsan H results from the polymerization of the above acid.

The basic properties of Rilsan are similar to those of other polyamides, but some of its characteristics are different. It is not subject to the same degree of hydroscopic expansion as are other superpolyamides. Under conditions where other superpolyamides will pick up a moisture content as high as 7.5% and even 10%, it will absorb only 1% moisture, resulting in excellent insulating properties.

Rilsan is a light material; its density is 1.04. It has a melting point of 186° C. The maximum temperature for continuous utilization in air, however, is 100° C, though it can easily be subjected to overheating up to a temperature of 140° C over relatively long periods of time.

Unlike many thermal plastics, the Rilsan coefficient of moisture absorption is extremely low thus resulting in the molded parts presenting remarkable dimensional stability and insulating properties. Plastics are not perfect insulating materials and when subjected to a continuous high voltage, they let through an extremely low but still appreciable current. The value of the resistivity of a specimen of standard Rilsan quality 3-mm thick which was exposed 4 days at 18° C to an atmosphere with a relative humidity of 80% as measured under a voltage of 1000 volts is 3×10 ohms/cm. Rilsan resistivity varies as the reciprocal of the temperature. At 60° C the resistivity is 1×10 ohms/cm. Rilsan possesses good insulating properties even when plunged into water.

Rilsan has high strength and offers excellent resistance properties to compression and flexural stresses, as well as good shock resistance properties and a good resistance to abrasion. Unlike many other polyamides which are attacked by Formol, Phenol, etc., Rilsan has good solvent resistance characteristics and is attacked only by Cresol.

The most common method of producing Rilsan parts is the injection moulding process, but Rilsan is also available in extruded shapes, such as tubes and strips and can be obtained in the form of powder for spraying on metallic surface, thus imparting to these surfaces its chemical and weather resistant properties and dielectric strength. In radio and electricity, this product has found wide use for insulating wires and cables. In the aircraft industry Rilsan is used as a protective material where it is particularly appreciated for its resistance to corrosion and its flexural strength.

Engineering Research Dividends

Recent theses submitted for advanced degrees from the College of Engineering, University of Washington, will regularly appear in abstract form in *The Trend*. Complete copies of these theses are available for reference at the University of Washington Library. Address inquiries to the Director of the Engineering Experiment Station, University of Washington, Seattle 5.

FANNELOP, T. K., "Design of a Hypersonic Shock Tube." M.S. in Aeronautical Engineering, 1957.

The feasibility of using hypersonic shock tubes for free flight simulation at high Mach numbers and stagnation temperatures is well established. This report describes the design of a hypersonic shock tube which will use both the reflected and nonreflected method for generation of hypersonic flows.

The tube has a circular driver and driven section, and the flow is expanded through a conical nozzle into an "open jet" test section. A second diaphragm is incorporated between the driven section and the nozzle inlet, in order to improve the starting process. By the use of interchangeable nozzle throat rings, the nozzle can readily be converted from a straight divergent to a convergent-divergent configuration.

The driver section has an inner diameter of 3 in. and a length of 6 ft; the driven section has an inner diameter of 2 in. and a length of 30 ft or less. The test-section diameter is 14¾ in. and the over-all length of the installation is approximately 40 ft.

Some future experiments for which this design should be particularly well suited are discussed. When the reflected method is used, it is suggested to let the incident shock wave be reflected from the second diaphragm rather than from the nozzle throat. By this method a full reflection can be ensured even for relatively large throat openings. The diaphragm will have to be properly selected so as to withstand the pressure rise behind the incident shock, but break as a result of the high pressure behind the reflected shock. For prediction of experimental results, complete performance calculations for the case AIR/AIR/AIR are given.

CHAHINE, M. T., "Use of Real Gases in a Shock Tube." M.S. in Aeronautical Engineering, 1957.

This study supplements the preceding report on design of a hypersonic shock tube. After a review of the basic equations for flow in shock tubes of uniform and variable cross section, the equations are solved for five gas combinations, namely, AIR:AIR, He:AIR, He:ARGON, H_2:N_2, and H_2:ARGON. The flow is assumed to be that of an ideal gas with constant heats, and to be isentropic. Results are reduced to a set of graphs and tables for the particular configuration of the shock-tube design.

KAMDAR, M. H., "Quantitative Determination of Glassy Phase in High Alumina Bodies," M.S. in Ceramic Engineering, 1957.

Microscopic, chemical, and X-ray diffraction methods for the determination of glassy phase in high alumina bodies are described. Chemical and X-ray diffraction methods gave an accuracy within one per cent of glassy phase and alpha alumina, respectively. The glassy phase in alundum grain (Norton Company) was determined as 17 per cent; while the alpha alumina content in Coors Porcelain Company's high alumina disc was 84 per cent. Three interplaner spacings 1.96 Å (202), 1.336 Å (125), and 1.2346 Å (119) were proved both theoretically and experimentally to belong to alpha alumina.

ALBERTSON, O. E., "Development of a Tertiary Algal Treatment Process," M.S. in Civil Engineering, 1957.

The principal concern of this research was to establish an economically feasible third-stage biological treatment of sewage-plant effluents to remove those nutrients which encourage growth of algae in receiving waters. A suitable type of algae, *Stigeoclonium stagnatile*, was selected for study. The initial research attempted to determine how fast phosphorus in a sewage effluent could be converted into algal cell tissue. The algal cells would then be separated by gravity from the sewage effluent. This process required several days, but with sufficient calcium concentrations in the sewage the phosphates could be co-precipitated. The primary function of the algae was to raise the pH to a level where the phosphate solubility is low. That biological utilization and absorption of phosphates by algae will not appreciably increase the removal efficiency was found to be true in the operation of a laboratory-scale pilot plant, where the efficiency of phosphate removal was a function of pH and calcium level. Data from the study indicate that a better knowledge of the factors influencing pH and, hence, efficiencies is desirable. The process shows promise, and a pilot plant adjoining a treatment plant is planned for next spring.

Notes and Comments

ENGINEERS IN THE NEWS

The annual Washington State Forestry Conference was held December 7, with **Dean Gordon D. Markworth** of the College of Forestry presiding. The program was directed toward the development of state natural resources. **J. L. McCarthy,** Professor of Chemical Engineering, took part in the panel discussion of new forest products industries, reporting on chemical derivatives, by-products, and problems of the pulp industry.

H. M. Hendrickson, Professor of Mechanical Engineering, attended the First International Saline Water Conversion Symposium, in Washington, D. C., on November 4, 5, 6, and read a paper, "Conventional Freezing Cycles and Economics." Professor Hendrickson supervised the project for desalting sea water by freezing, sponsored by the Office of Saline Water, U. S. Department of the Interior. The project was concluded in May, 1956.

Technical Report Writing by **J. W. Souther,** Associate Professor of Humanistic-Social Studies, was issued by John Wiley and Sons in November. The book, of 70 pages, presents technical report writing as a special problem in design, following the steps of Analysis, Investigation, Design, and Application. It deals with such factors as form, writing style, methods, and use of illustrations. Diagrams and a report-writing check list provide visual assistance for the reader who is concerned with technical communication.

The 37th annual meeting of the Highway Research Board took place in Washington, D. C., January 6 to 10. The following members of the Department of Civil Engineering appeared on the program of various divisions: *Traffic:* **E. M. Horwood,** "City Center Goods Movement"; *Soils:* **R. G. Hennes, S. E. Hawkins,** and **E. L. McCoy,** "An Appraisal of Measures for the Improvement of Slope Stability"; **W. D. Finn** and **Bjorn Strom,** "The Nature and Magnitude of Soil Pressure." From the Department of Geography, **W. L. Garrison** and **D. F. Marble** were authors of a paper, "The Economic Analysis of Highway Networks: A Linear Programming Formulation," on the program of the division of *Economics, Finance and Administration.* **R. G. Hennes,** Professor of Civil Engineering, presided at this session and at a later session of the same division discussed "The Role of the University in Highway Research."

J. I. Mueller, Professor of Ceramic Engineering, attended the 10th Pacific Coast Regional Meeting of the American Ceramic Society which was held at San Francisco, October 17-18-19. He presented a paper, "Quantitative Determination by X-Ray Diffraction of the Glassy Phase in High Alumina Bodies," before the Electrical Symposium. Co-author was graduate student **B. H. Kamdar** who received his M.S. in Ceramic Engineering in December.

J. L. Bjorkstam, Assistant Professor of Electrical Engineering, attended the meeting of the West Coast Division of the American Physical Society, held at Stanford University, December 19-21. Professor Bjorkstam presented a paper on "The Deuteron Magnetic Resonance in KD_2PO_4."

URBAN ROAD ECONOMIC IMPACT STUDY

Research seeking answers to the effects of urban freeways on land use and the analysis of urban freeway systems is part of the scope of a new project initiated by the Civil Engineering Department.

The State Highway Commission and Bureau of Public Roads are joint sponsors of the research, the cost of which is being carried entirely by federal funds. The research is part of the National Highway Cost Allocation Study.

The project is of an interdisciplinary nature, involving personnel from the fields of urban geography and highway planning. Professor William L. Garrison, Department of Geography, is directing one part of the study dealing with the impact of highways on land use, and Professor Edgar M. Horwood, Department of Civil Engineering, is directing the second part, concerned with freeway system analysis. Professor Robert G. Hennes is the project initiator.

An appropriation of $25,000 has been made to cover cost of the project up to September 30, 1958.

NEW SEISMIC STATIONS ESTABLISHED

TWO AUXILIARY STATIONS for the seismological investigations carried on by the Department of Geology are nearing completion at Longmire and Tumwater. They will help to clarify the peculiar crustal structure of the Puget Sound area and its relation to seismic activity in this region.[1]

The latest results of using the correlation between gravity surveys and seismological results to interpret the seismograms obtained at the University Station[2] are set forth in a paper, "Crustal Structure of the

(Continued on page 28)

[1] See "Gravimetry at the University of Washington," by John W. Jones, *The Trend in Engineering,* July, 1952.

[2] "Earthquake Investigation at the University of Washington," by Frank Neumann, *Ibid,* October, 1956.

Damaging Earthquake and Blast Vibrations

(Continued from page 10)

amount; cracked plaster somewhat, especially fine cracks in chimneys in some instances; broken dishes, glassware in considerable quantity, also some broken windows; fallen knickknacks, books, pictures; overturned furniture in many instances. Grade VI is felt by all, both indoors and outdoors. If everyone (in a sizable community) is awakened, the intensity is rated VI without further supporting Grade VI evidence. The average ground acceleration applicable to this grade is 0.064 g on the basis of the writer's investigations, and this also should be associated with a frequency of 3 cps.

An important question arises as to how accurately the instrumentally recorded accelerations represent the ground motion at the sites of reported maximum intensity or damage. Some of the approximately fifty accelerographs of the Coast and Geodetic Survey are on rock, some are on firm soil, and some are on the most loosely consolidated soil in the community. In developing the relationship between intensity and acceleration, the writer thought it best to use an average value of the recorded accelerations even though higher accelerations were available for correlation with the various grades of intensity. (See Fig. 3 in "Earthquake Intensity and Related Ground Motion.") If, however, we accept only the highest values of acceleration corresponding to the various intensities, it could be considered as compensating for those situations in which, owing to differences in location, the accelerograph did not necessarily register the motion corresponding to the maximum intensity reported. This would increase all of the accelerations about 75 per cent.

Judging by the character of the phenomena associated with these highest values of acceleration (involving only three earthquakes), it would not seem too far amiss to consider them associated with the upper ranges, or the more violent phases, of the Grades to which they apply. If one uses the original acceleration applied to Grade VI (0.064 g average for the grade), considers Grade 6½ as the peak activity in Grade VI, and takes the exponential character of the intensity-acceleration relationship into account, a peak value of 0.090 g is obtained as the highest possible acceleration applicable to Grade VI. If one takes the original average acceleration of 0.064 g and increases it 75 per cent to reconcile it with the maximum values obtained in the intensity-acceleration relationship, a value of 0.111 g is obtained. From these two considerations it would seem that, for all intents and purposes, 0.10 g (average of 0.090 and 0.111 g) could be accepted definitely as a potential "falling plaster" acceleration. It would correspond to the most violent motion that can be assigned to Grade VI.

Following this type of argument through for Grade V, it may be similarly concluded that 0.04 or 0.05 g. can be considered a potential "plaster cracking" acceleration which could be reconciled with either the peak of Grade V intensity or the lowest range of Grade VI. All of Grade VI could be looked upon as covering potential "plaster cracking" intensity in the lowest range (0.04 or 0.05 g) and potential "falling plaster" intensity in the highest range (0.10 g). But even these figures cannot be considered so final that further modification must be considered improbable. Special importance must be attached to this phase of the discussion, because earthquakes offer a much more prolific source of bona fide vibration damage than blasting operations in which reported damage is often open to question.

Discussion of Results Reported in the Three Papers

In order to compare the results obtained by Crandell, the U. S. Bureau of Mines, and the writer, Fig. 1 was prepared so that they could all be illustrated graphically on frequency and acceleration scales common to all. The scale shown at the bottom of Fig. 1 shows vibrations expressed as "frequencies" for frequencies from 1 to 50 cps, and as "periods" for periods from 0.1 to 4.0 second. The overlapping zone makes it possible to read a vibration time as either a frequency or a period. At points a, b, and c, the frequency-period scale has been changed in order to show the earthquake data in greater detail. Acceleration is shown on the logarithmic ordinates in terms of fractions of gravity. At the top of the illustration appears the approximate number of stories required in a building to yield the building vibration frequency shown in the frequency-period scale at the bottom of the chart. The building amplitude and building period are indicated by A_b and T_b, respectively. Thus, a five-story building might be expected to have a natural frequency of about 2 cps. In practice the correct value can be determined only by measuring the building period.

The left side of Fig. 1 shows the results of Crandell's work. His investigations were all restricted to a frequency range of 10 to 60 cps. His curves defining the caution zone are expressed in units of gravity instead of ft/sec² and are equivalent to the energy-ratio factors of 3 and 6 used in his paper. They have been extended into the low-frequency zone, to 4-seconds period, to see to what degree they can be reconciled with earthquake results. It will be shown later that the results are encouraging.

It will also be seen that Crandell's evaluation of high-frequency vibrations that are "severe," "troublesome," and "noticeable" tie in fairly well with similar sensations indicated in the Modified Mercalli Intensity Scale and the accelerations assigned to the various grades by the writer in "Earthquake Intensity and Related Group Motion." It appears, however, that, for the same type of sensation experienced, Crandell calls for a generally lower degree of energy than is indicated on the Earthquake Intensity Scale and its equivalent ground motions. This assumes, of course, that Crandell's criteria for high-frequency vibrations can be legitimately extrapolated into the lower frequency earthquake zone. While Intensity V vibrations might be considered "severe" in the central area of a non-destructive type of earthquake (where the higher frequency vibrations would predominate) it is debatable whether "troublesome" vibrations could be attributed to an intensity lying between III and IV. The significant thing is that no great divergence exists between results obtained through two entirely different approaches to a common problem.

As previously stated, the principal contribution of the Bureau of Mines' investigations is Table 6 in Bulletin 442 which enables one to make an estimate of the amount of ground vibration to expect from a given blast. In their efforts to evaluate a damaging vibration the investigators were admittedly handicapped by an absence of damage in the buildings that were subjected to the observed vibrations. As a result much of their work was directed toward impressing vibrations (with a heavy shaking machine) on buildings and panels up to the point of damage, but just how such results should be interpreted in terms of equivalent ground vibrations is open to discussion. In both Crandell's work and that of the Bureau of Mines, it would seem that the maximum motion of a building and the motion of the ground were considered at least roughly identical, and this would be true for high-frequency vibrations as indicated in Fig. 3A.

The writer, however, does not believe this same principle is applicable to panel vibrations. Evidence that seems to support this view is found in the Bureau of Mines' statement that damage to panels did not occur when the shaker reached resonance frequencies but when there was about 50 per cent difference in these frequencies. It seems that in such cases a "hammering" action was built up when the (natural period) panel vibrations and the shaker vibrations were out of phase, and this seems to have caused the damage. A parallel phenomenon is indicated during earthquakes when, for instance, the steeple portion of a church begins "hammering" the auditorium portion because of differences in their phase responses to the earthquake vibration. The graph inserted in Fig. 1 summarizes the wall-panel and floor-panel results in a way that makes it possible to compare them with Crandell's damage zone. It will be noted that some panels are damaged before Crandell's caution zone is reached, a further indication that the alleged damaging accelerations are too low and that damage was caused primarily by the battering action of the shaker on the vibrating panels. The fact that these tests covered a frequency range from 6 to 40 cps instead of the representative frequency of 10 cps indicated on the chart, makes little material difference in this conclusion because 10 cps is close to the average frequency measured.

The caution zone indicated in the Bureau of Mines report lies between 0.1 and 1.0 g, but the restrictions in its Table 7 are shown by the shaded area in Fig. 1. It can be seen how the shaking-machine wall damage may have influenced such a wide choice of accelerations to define this zone. All accelerations above those indicated by the shaded border would be considered damaging and all those below it safe. In view of the results obtained by Crandell in defining a caution zone, the shortage of bona fide vibration damage in the Bureau of Mines investigations, and the earthquake results obtained at generally lower frequencies than those covered by the Bureau of Mines, the writer would, for the time being, give greater weight in this frequency area to Crandell's criteria.

In the earthquake portion of Fig. 1, the accelerations and the periods indicated for the various grades of the Modified Mercalli Earthquake Intensity Scale of 1931 are taken from the writer's booklet, "Earthquake Intensity and Related Ground Motion." The accelerations indicated correspond to an average period of 0.33 second or 3 cps. This was the average of a group of "maximum acceleration" periods ranging from 0.1 second to 1.2 second. While it was evident at that time that the longer-period waves in this group were in general associated with lower accelerations, the pattern of period-acceleration distribution was too irregular to deduce from it any distribution characteristic such as Crandell's "energy ratio" in which $(\text{acceleration})^2/(\text{frequency})^2$ is a constant. The booklet does show very clearly, however, that, in the analysis of any particular record, intensity is a function of both acceleration and period; significantly, this relationship differs but little in general form from the energy function of Crandell as expressed by $(\text{acceleration})^2/(\text{frequency})^2$.

For these reasons it seems a legitimate procedure to assume, at least tentatively, that the acceleration-frequency relationship that expresses a given earthquake intensity might be of the same general form as the acceleration - frequency relationship that

expresses constant kinetic energy. Since, as previously stated, 0.05 g (at 3 cps) could be considered (from earthquake studies) a plaster-cracking acceleration, and 0.10 g a falling-plaster acceleration, curves were drawn approximately through these points parallel to the extrapolated Crandell curves which define the limits of "caution" vibrations. These curves in Fig. 1 are designated "plaster-cracking earthquake vibrations" and "falling plaster earthquake vibrations."

The fact that the "plaster cracking" and "falling plaster" ground vibrations obtained from earthquake data fall far beneath the extrapolated Crandell curves defining damaging motion, and even largely beneath those of the Bureau of Mines, requires explanation. The writer believes that damage during earthquakes, especially in the lighter variety of damaging shocks, is due largely to resonance or partial resonance and a resulting increase in building motion over and above that of the ground. It has already been stated that a factor of 4 could be considered representative of this increase. If, therefore, the damaging ground motions found in earthquakes are quadrupled, they will represent maximum building accelerations and these in turn will be found to correspond closely to the motions that Crandell considers potentially damaging. They correspond to the same energy factors that he considers damaging. If a plaster-cracking earthquake acceleration is quadrupled, it will lie in Crandell's (extrapolated) "caution" zone. If a "falling plaster" earthquake acceleration is quadrupled, it will fall well inside of Crandell's "danger" zone. The writer believes that this represents a reconciliation of what appear to be serious discrepancies between what various investigators have been designating potentially damaging vibrations. The significant point is that it is the kinetic energy represented in the *building* vibration that is the measure of the damaging potential and not necessarily the energy indicated in the ground motion.

The dotted period-acceleration envelopes in Fig. 1 for six damaging earthquakes, when studied in relation to the provisionally designated 'caution" and "damage" zones, reveal a wealth of information that has special significance in the field of engineering seismology. In the first place, they show how fickle, yet how very important, a dominant earthquake ground period is. In one case a particular period may represent most of the damaging potential; in another case it may not even be present. The factors that govern dominant periods are important to know, and much research is needed to clarify the period enigma. There seems to be little doubt that it is controlled in large part by the pattern of crustal structure and surface geology beneath the site under consideration. In order to study this relationship expeditiously, and because of their close relationship to earthquake spectra, period-acceleration envelopes should be a primary requirement in the interpretation of important strong-motion records of destructive earthquakes. The writer knows from personal experience that this can be done satisfactorily if velocity records are computed through integrating instrumental accelerograph records, for only then are the periods inherent in a complex earthquake motion revealed in sufficient detail and quantity to construct satisfactory period-acceleration envelopes. While other methods of period analyses are possible, it is doubtful that any of them would be less costly than the method suggested. The few spot readings published by the U. S. Coast and Geodetic Survey offer the interested researcher little to work on in investigations of the kind presented in this paper and in other analytical studies.

Figure 1 shows how high-frequency earthquake waves of 5 to 10 cps can build up resonant vibrations in low residential structures. Ground vibrations of this frequency may also result from blast vibrations passing through deep alluvial formations. The cause of excessive damage on deep alluvial soils may be due as much to the existence of resonant ground and building periods as to the greater ground amplitudes generally found on such formations. Both factors serve to make alluvial soils poor vibration risks. In this frequency zone low structures tend to react in the manner shown in Fig. 3B (indicating resonant vibration), while taller buildings react with less violence, as in Fig. 3A. Ground vibrations of 5 to 10 cps are more likely to be 4 cps in epicentral areas, disappearing at epicentral distances of approximately 25 miles and more.

In the frequency range from 1 to 5 cps, one finds not only the frequency (3 cps) associated on the average with the highest earthquake accelerations, but the natural periods of a great variety of commercial structures, schools, and other public buildings in which earthquake damage so frequently occurs. This is a frequency zone in which damaging resonant vibrations may depend on just how closely a particular building frequency matches one of the dominant ground frequencies. If the building frequency is considerably less than that of the dominant ground waves, the building will react as in Fig. 3A. If it is greater, the reaction will be as in Fig. 3C. Ground frequencies of 1 to 5 cps may be present over a very large part of a shaken area, with the frequencies generally decreasing with increasing epicentral distance. It is in this frequency zone that one may generally look for the greatest amount of earthquake damage.

As one goes into the frequency zone below 1 cps, into the long-period zone, resonant vibrations will be found only in tall buildings and such special engineering structures as bridges and elevated water

tanks. Here one gets into the zone of high-amplitude vibrations, and damage due to deformation seems more likely to occur than in the case of vibrations of higher frequency. It is well to remember that the maximum ground displacement recorded on an accelerograph in this country was associated with a period of 4 seconds. If the ground vibrations include periods similar to those of certain tall structures, the chances are that the amplification factor will be greater than 4, especially as one recedes from an epicentral area into a zone where the ground vibrations are less complex and more conducive to large resonance factors. For ground periods considerably less than building periods, the building reaction will be as shown in Fig. 3A. For ground periods that are greater, the reaction will be as in Fig. 3C. For tall buildings, it is believed that deformations of the latter kind can be damaging if building and ground periods do not differ by too wide a margin.

When one considers that two or three building reactions of the types just outlined may affect a structure simultaneously, the complexity of the problem becomes apparent. These reactions may be additive or may tend to nullify each other, thus accounting in part for the frequently observed freakish character of earthquake damage. However, if one considers the various factors responsible for earthquake as well as blast damage, it still may be possible to place one's finger on the particular type of ground motion and building deformation that causes the greatest damage in a particular structure.

If one refers to earthquake spectra for information on the theoretical reaction of structures to complex earthquake motions, he learns, as previously stated, that when a constant damping factor for all oscillators (and buildings) is assumed the reaction (amplification) is quite uniform over a wide range of oscillator periods. The consideration of individual structural characteristics such as are outlined in the preceding paragraphs may seem superfluous. But it is yet to be shown that all structures can be safely assigned a constant damping factor such as 0.2; and if they cannot, then it is equally clear from spectrum results that a wider range of building reactions can be expected than can be shown on any spectrum curve covering a single damping factor. In view of the complex pattern of building damage actually experienced, there would still seem to be merit in studying the response characteristics of individual structures, as in the preceding paragraphs, rather than assigning to them some arbitrary damping factor that may or may not be correct. It seems just as logical to assume from instrumental observations that a certain degree of amplification may be expected as it is to assume a particular damping factor that will theoretically yield that degree of amplification.

In Fig. 1 the period-acceleration envelopes as a rule show certain frequencies that stand out over the others. The fact that curve A, for the El Centro earthquake of 1940, does not show such characteristics is due more to the difficulties of making a period analysis than to any definite knowledge that there were no dominant periods. Curve A has been changed from a similar curve drawn in 1940 (and reproduced in "Earthquake Intensity and Related Ground Motion") because certain derived accelerations between 0.3- and 1.0-second periods are not supported by direct readings made on the partially illegible accelerogram. This change makes the El Centro curve in Fig. 1 consistent in general pattern with the other period-acceleration envelopes.

For periods greater than 0.3 second, Curve A shows that the energy of the ground motion is only slightly greater than that indicated in a number of other shocks. For El Centro, the Coast and Geodetic Survey reports that "a number of old brick buildings were so badly damaged that they were condemned. Damage was chiefly to old brick construction, to walls that were not reinforced or tied to the structures, and to balconies projecting over sidewalks. There were a few breaks in the water mains, but practically no damage to the water plant or to sewer lines." Several individual reports indicate that fall of plaster was rather widespread. The greater damage at Calexico and Brawley was apparently due to their closer proximity to a number of damaging aftershocks. In the case of the Long Beach, 1933, record, a 1.0-second wave was discernible on the accelerograph record, but there may have been a similar wave in the lost portion of the record with a higher acceleration than that indicated in Fig. 1.

While acceleration has been stressed in the preceding paragraphs as the damaging agent, Fig. 1 also shows the displacement aspect of the problem. The displacement curves shown on the chart correspond to Crandell's two energy curves that outline the "caution" zone. Parallel curves could also be drawn to represent other degrees of vibrational intensity. It so happens that the displacement scale (in inches) on the right side of the chart duplicates, ordinate for ordinate, the numerals that express ground accelerations in terms of gravity on the left side of the chart. For any combination of acceleration and frequency one can determine the corresponding displacement from the equation: $A_e = a/4\pi^2 n^2$. The formula in Fig. 1 is applicable when the units shown on the chart are used.

By estimating relative ground and building displacements one may get an idea of the magnitude of the deformation to which a building is subjected. If this exceeds what engineers consider a safe limit,

damage will result. While building distortion may assume several patterns, such as shearing and flexural deformation, it is believed that its general magnitude can be estimated fairly well in the cases of type A and type C responses illustrated in Fig. 3, since either the building or the ground motion will often be relatively small. In the Fig. 3C type of deformation both building and ground may be displaced through large amplitudes, yet the building deformation may be insignificant. While the magnitude of this deformation is indicated in Fig. 2 (right-hand side), it can also be calculated as previously stated by a simple formula if one remembers that the computed deformation refers to the center of oscillation of the building and that the formula holds only when the ground period, T_e, is at least two or three times the building period, T_b. If A_e is the ground displacement and A_b the displacement of the center of oscillation of the buildings, then $A_b = A_e\ (T_b/T_e)^2$.

Referring to Fig. 1, let it be assumed that a four-story building having a period of 0.4 second was shaken by ground waves of 1.0-second period and 0.06-g acceleration, as at Seattle in the Puget Sound earthquake of 1949, epicentral distance 33 miles. The ground displacement would be 1.5 cm. Using the above equation, the displacement of the center of oscillation of the building relative to its base would be 0.24 cm., or perhaps 0.35 cm. (or 0.14 in.) at the roof level. Since the amplitude of the total roof displacement (not the deformation) is thus increased by nearly 25 per cent (0.35/1.5) over that of the ground, the roof acceleration would be increased in the same ratio, from 0.06 to 0.075 g which would place the maximum building acceleration practically on the provisional danger line. These accelerations would decrease in lower buildings having shorter natural periods than 0.4 second and increase in taller buildings having longer natural periods, up to periods producing resonance. While it is known that much damage was caused in Seattle and the Puget Sound area by this earthquake, some uncertainty arises from the fact that the seismograph that registered the acceleration quoted here was located several miles south of downtown Seattle on the Duwamish River flats. In a similar manner one may use the data shown in Fig. 1 to speculate on an infinite number of hypothetical conditions, but the only speculation that can be adequately substantiated concerns those cases in which instruments are placed on the top floors of structures to verify estimated building motions.

In conclusion the writer is convinced that, insofar as the evaluation of a damaging earthquake and blast vibration is concerned, no real discrepancies exist between his results and those of Crandell and the U. S. Bureau of Mines that cannot be satisfactorily reconciled. Moreover, Crandell's "energy ratio" will serve provisionally as a criterion for earthquake damage if it is extrapolated into the range of earthquake frequencies and made applicable to maximum building vibrations rather than to ground vibrations alone. This approach, perfected to a higher degree than is possible at this time, would be of value in estimating the lateral forces exerted on buildings during damaging earthquakes and in estimating structural deformations. It would improve on the present system of designing structures to resist static forces (such as 0.1 g) in that it would take the periods of structures into account, in this respect paralleling the proposed earthquake spectrum method of predicting structural stresses. While it is not asserted that this study offers an airtight formula for evaluating a damaging vibration, the type of approach described apparently suggests a straightforward and promising means of developing such a formula.

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NEW SEISMIC STATIONS ESTABLISHED

(Continued from page 23)

Puget Sound Area," presented by Seismologist Frank Neumann, before the meeting of the International Geodetic and Geophysical Union in Toronto last September. The paper reveals not only that the wide spread of negative gravity anomalies is related to an abnormal depth of low-velocity (low-density) rocks, but that a massive intrusion of higher density rock between Seattle and Tacoma reaches a peak where the pull of gravity is a maximum for the area. Professor George H. Woollard of the University of Wisconsin reported that this area is also marked by an outstanding magnetic anomaly.

Further evidence on the existence of low-density crustal layers two or three times the normal thickness of continental layers is indicated in a number of recent investigations showing that there is a delay of approximately two seconds in the time required for seismic compressional waves to reach the University Seismograph Station in Seattle.

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